End Game Enhancement Using Reflexive Decision Making

Presented To

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Funding through — Munitions Directorate, Elgin AFB, SBIR Program

Outline

- Orbital Research Background
  - Company History
  - Programs
- Advanced Control Program Overviews
  - Ship automation
  - Swarm Intelligence for Air Vehicles
  - Biologically Inspired Collision Avoidance and Target Seeking Systems
- End Game Enhancement Using Reflexive Decision Making on Loitering Munition
  - Training of Neural Networks with Genetic Algorithms
  - Simulation Results
    - » Stationary Targets
    - » Moving Targets
- End Game Enhancement Flight Demonstration

Company Background

- **Founded:** February, 1991
- **Mission:** To find new and innovative technological solutions in advanced controls and microdevices for various military and commercial applications.
- **Focus:** To transition basic research and development technologies from the laboratory environment to hardware platforms.
- **Location:** 673G Alpha Drive, Cleveland, Ohio
- **Employees**: Twenty employees (sixteen full-time) and twelve consultants
- **Core technologies:**
  - Micro Devices and Sensors
  - Advanced Controls

Orbital Research is a Small Business but….

- **In business for 10 years**

Inc.

- **Top 500** – selected as one of the fastest growing companies in the US to be awarded *06/02*

THE WEATHERHEAD 100 OUTSTANDING GROWTH COMPANY

- **"Weatherhead 100 - Outstanding Corporate Growth Award,"** Weatherhead School of Management 1999, 2000 and 2001

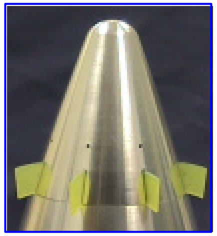
THE INNER CITY 100 ICIC Inc.

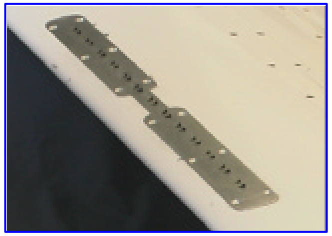
- **"Inner City 100 Award"** from **Inc.** Magazine's Initiative for a Competitive Inner City in 1999, 2000, and 2001

Micro Devices and Sensors

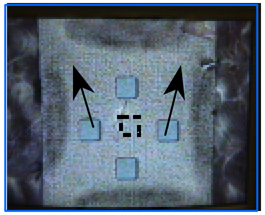
MEMS Microvalves

Flow Control Devices

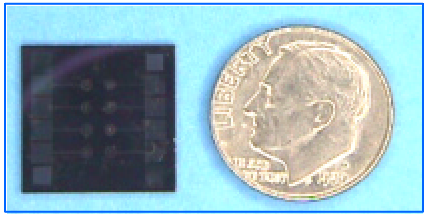




Missile and Airfoil Control

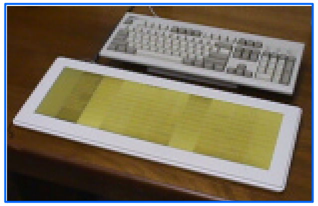


MEMS Microvalve

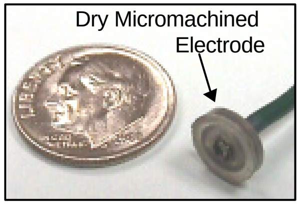


Array of 8 Microvalves

Medical Devices



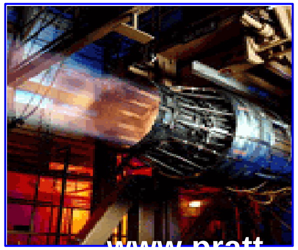
Refreshable Braille Display System



Physiological Electrode

Micro Pressure Transducers

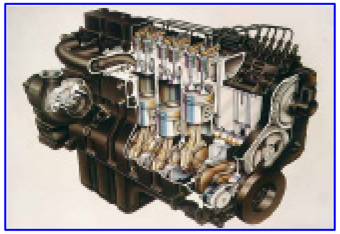
In-Situ Pressure Transducers for Turbine Engines



- dynamic pressure measurement
- Stall detection
- Reduced emissions

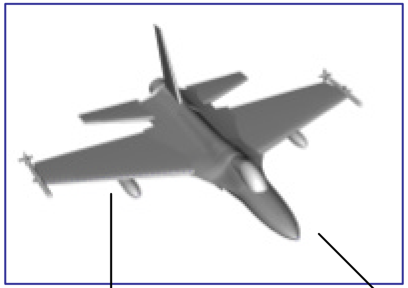
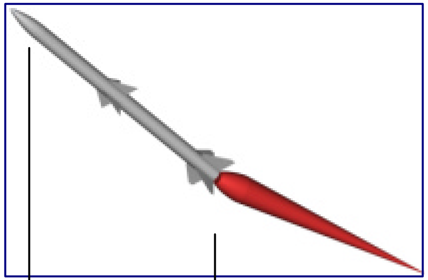
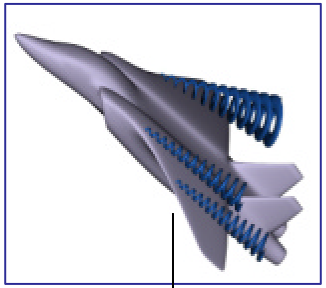
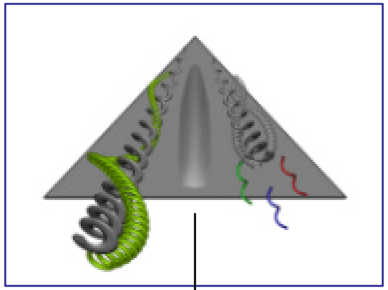
- Fuel efficiency
- Blade-tip passing
- Engine health monitoring
- Flame-out detection

In-cylinder Pressure Transducers for Diesel Engines



- Linear output over wide range of strain
- High sensitivity
- Operates above engine temperature
- Robust design for combustion monitoring

Active Flow Control Overview

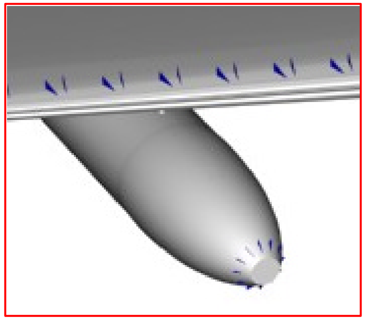





SEPARATION CONTROL

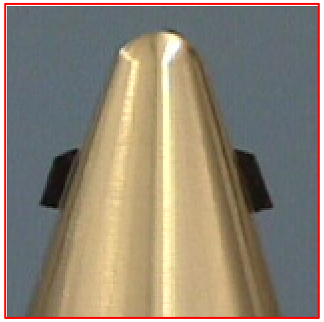
FOREBODY CONTROL

THRUST VECTORING

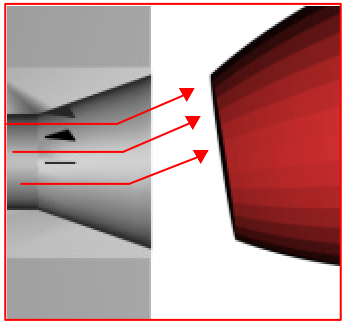
VORTEX CONTROL



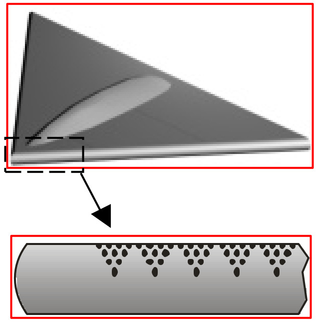
Deployable Flow Control Devices (DFCDs)



Enhanced Missile Guidance

Jet Vectoring Using DFCDs



Micro Adaptive Suction Control (MASC)

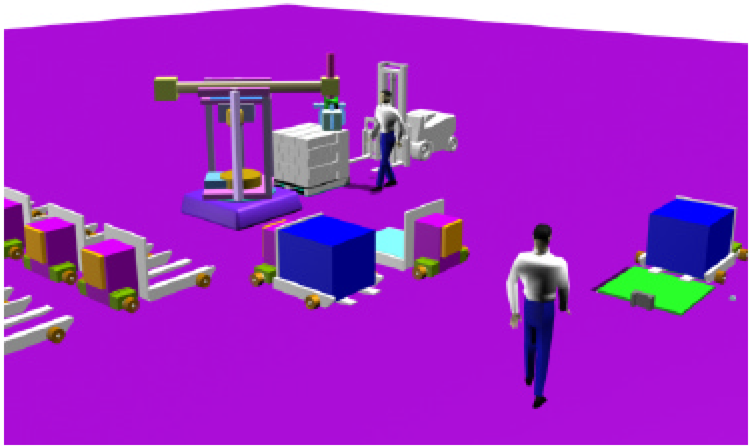
- **AIRFOIL RESEARCH**
- **DELTA WING RESEARCH**
- **MISSILE RESEARCH**

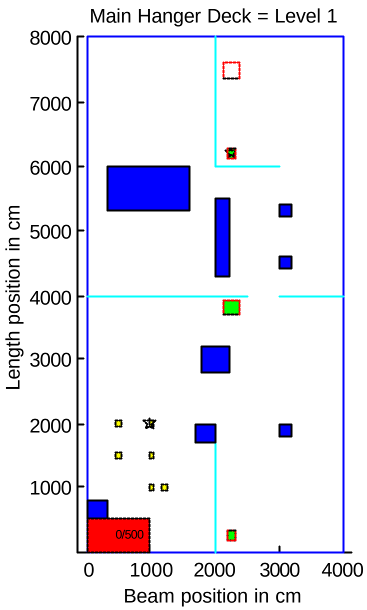
Experimental Fluid Dynamics (EFD)

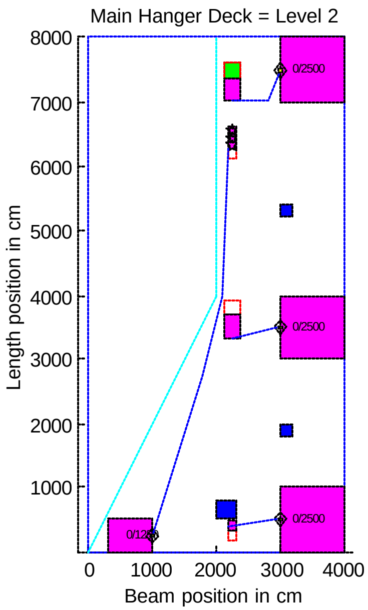
+

Computational Fluid Dynamics (CFD)

Control Solutions for Material and Weapons Handling on Navy Ships





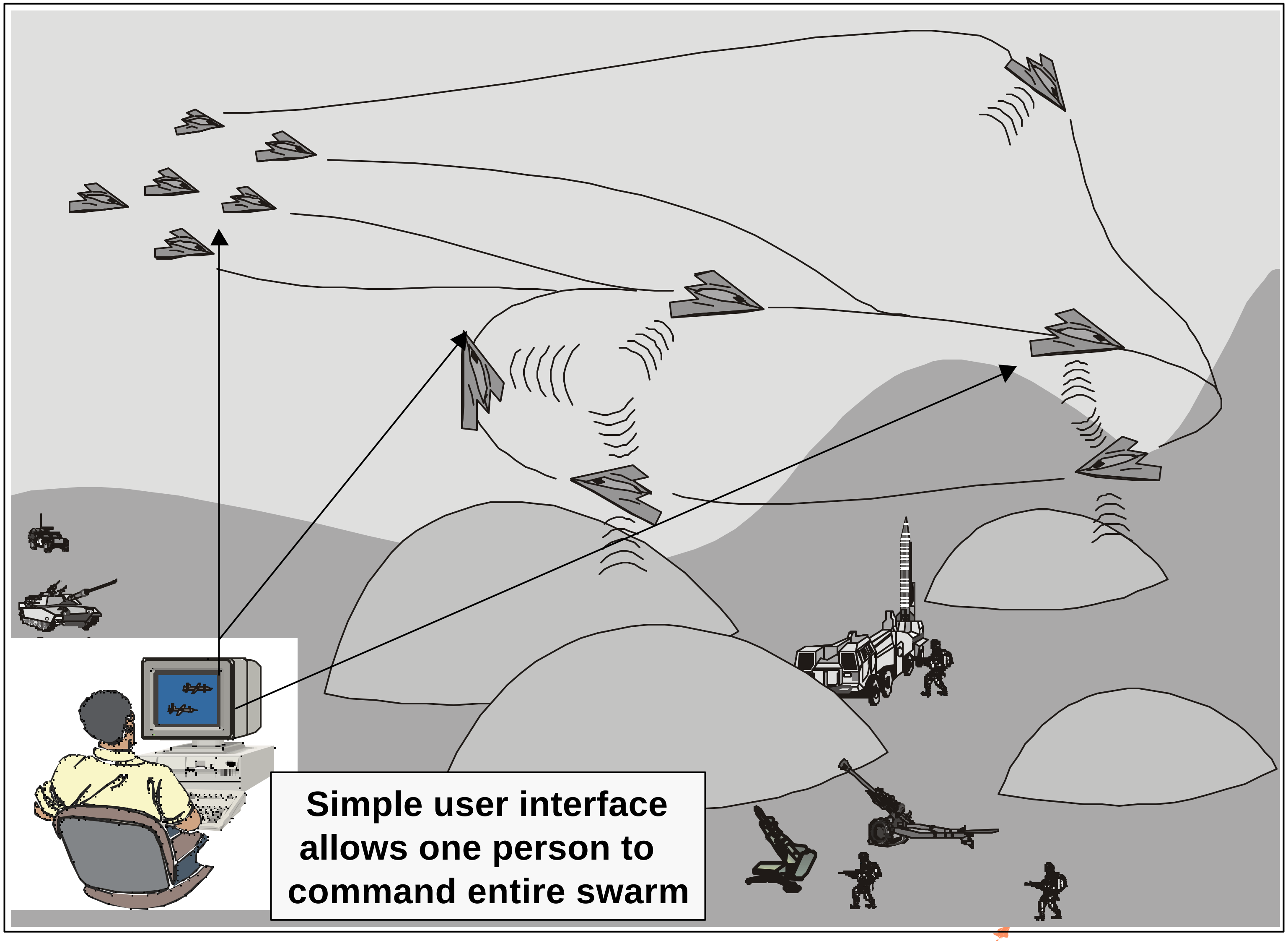


Handling System Components

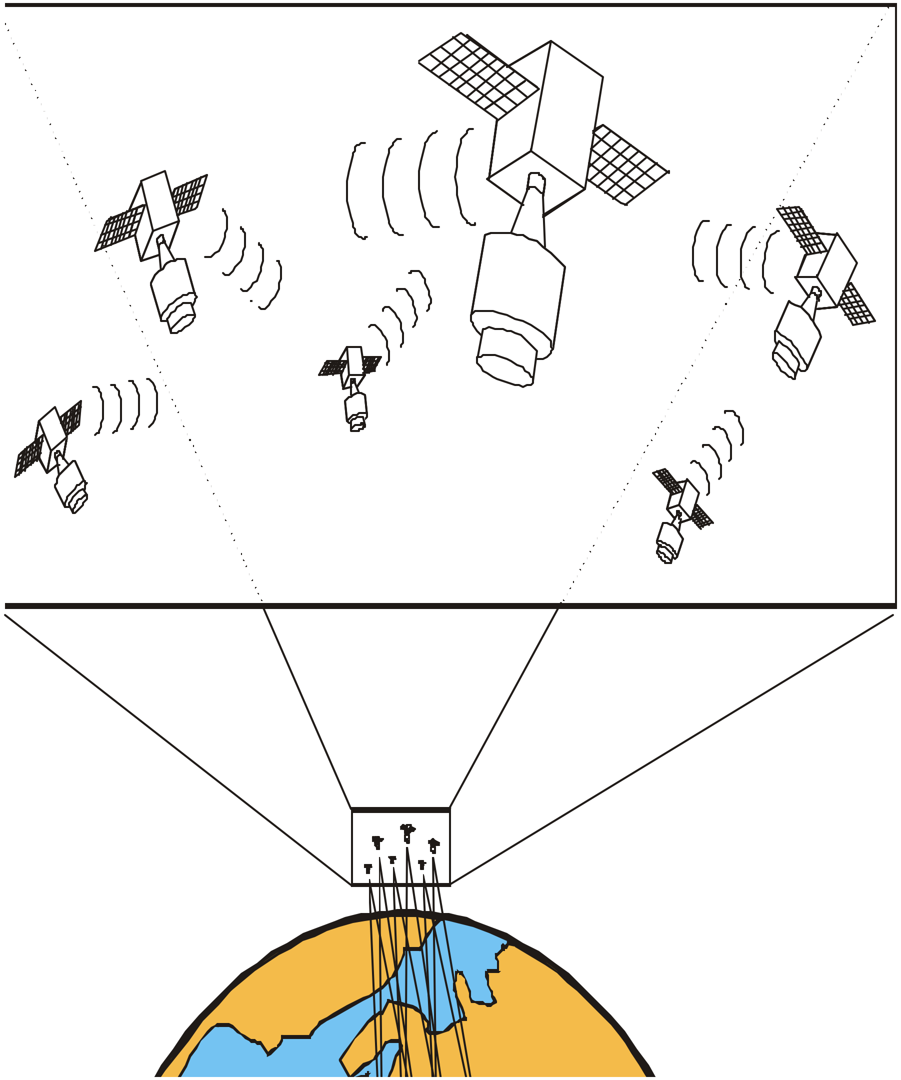
- **Autonomous Mobile Cargo Handling Units**
  - Swappable Battery Packs for Power
  - Essential Spatial Awareness and Navigation
  - Capable of Handling Up To Maximum Std. Container Weight ~5000 lbs.
- **Depalleting Handlers**
  - Modeled on COTS Pick&Place Robotics Systems
- **Vertical Conveyor Systems**
  - Replaced with Linear Motor Actuated Small Automatic Elevators
- **Automated Storage Rooms**
- **Horizontal Conveyors**
  - Based on Low-Profile ‘Fold-Down’ Linear Motor Systems
- **Weapon Magazines**

Group Coordination : UAVs / Loitering Munitions Control:

Swarm intelligence algorithms synergize cooperative behavior between UAVs;
Agents work collaboratively for optimal mission performance



Group Coordination: Microsatellite Constellations



Features:

- *Group behavior algorithms enable collaboration of swarms of microsatellites*
- *Rule based commands for tasking of individuals*
- *Fuzzy system identification for adaptive sensor fusion dictating rule based commands*

Benefits:

- *Decentralized and rapidly reconfigurable control principles*
- *Adaptability to changes in mission and mission resources (e.g. number of satellites)*
- *Ability to generate new robust rule bases for variable missions*

Autonomous Munition Guidance

- Three recognized fundamental phases of munition flight:
  - **Midcourse** - from launch until target acquired
  - **Terminal** – when target acquired
  - **Endgame**- last one second or less of flight
    - » Separate problem due to speed of correction
    - » Control inputs (thrust) may be unreliable
    - » Missile guidance failure most likely to occur during endgame
- Improvement in performance during endgame engagement is necessary
- Biology offers insights for potential improvements

Critical System Operating Assumptions

- Terminal guidance has piloted the air vehicle into a viable endgame position
- Linear air frame operating response for endgame bounds
- LADAR data on target position provided
- Constant forward thrust

End Game Enhancement using Neural Nets and Genetic Algorithms

Biologically Inspired Target Seeking Reflex for Autonomous Munitions

Program Goal:

- Provide rapid target seeking and in-flight mission re-planning capabilities for autonomous munitions by developing a set of reflexes with similar capabilities as biological organisms

Benefits:

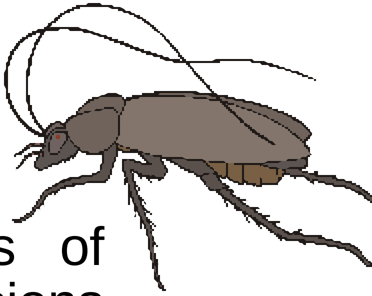
- Instantaneous target path generation and tracking
- Efficiency of trajectory generation not inhibited by vehicle complexity
- Capability to incorporate any number of optimization characteristics
- Ability to react to/consider several threats simultaneously
- Reflexive behavior is context dependent (updated based upon vehicle state)
- Passive system enables smooth autopilot interface

Need for Endgame Enhancement

- Autonomous air vehicles are dependent on automatic control
- Rapid planning needed during end game for precision guided munitions
- Necessary features of such a system include:
  - accurate autorouting capability
  - incorporation of vehicular and environmental constraints into path generation
  - perform path-planning functions within strict time constraints

Orbital Research Program

- Prove Genetic Algorithms can generate a set of inputs which fly the munition to a point where a projectile would strike near center of target
- Utilize Neural networks which hold great promise for use in endgame due to their capability to represent complex data in compact structures for fast throughput
- Lay groundwork for development of control architectures for autonomous air vehicles that **expand scope and utility for other air vehicles**



Motivation: Key Abilities Inspired from Nature

- **Sensor Integration: animals** integrate large amounts of sensory information from multiple sensor modalities - decisions must be made rapidly. Munitions need to process many sources of sensor data to come up with appropriate response from actuators.

- **Context Dependent Behavior:** animal's reactions are continuously updated based upon **internal** physiological state and **environment**– leg extended vs. control surface position. Munitions need to increase their efficiency and adaptability.

- **Multi Constraint Incorporation:** animals are capable of optimization within a host of varying conditions (missing legs). Vehicular dynamics and constraints (such as varying flight envelopes) need to be addressed.

- **Evolved Pattern Response**: animals have thousands of generations of natural selection whose results are incorporated into their responses. Pre-developed reflexes need to be combined and tuned for robust instantaneous reactions to every situation encountered during end game

Motivation Summary:

Key Biological Abilities Inspired from Nature

a) well-adapted to the environments in which they operate,

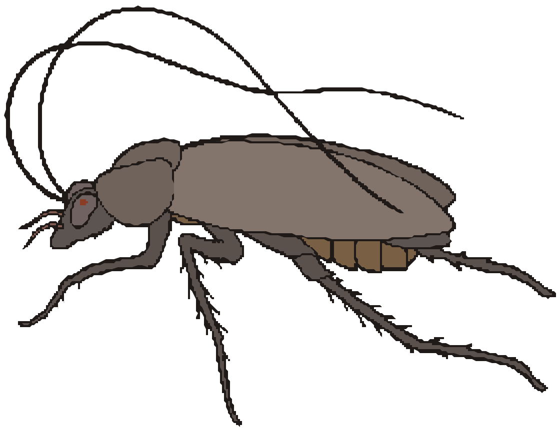
b) exhibit an impressive efficiency and flexibility,

c) are very robust to contingency and damage;

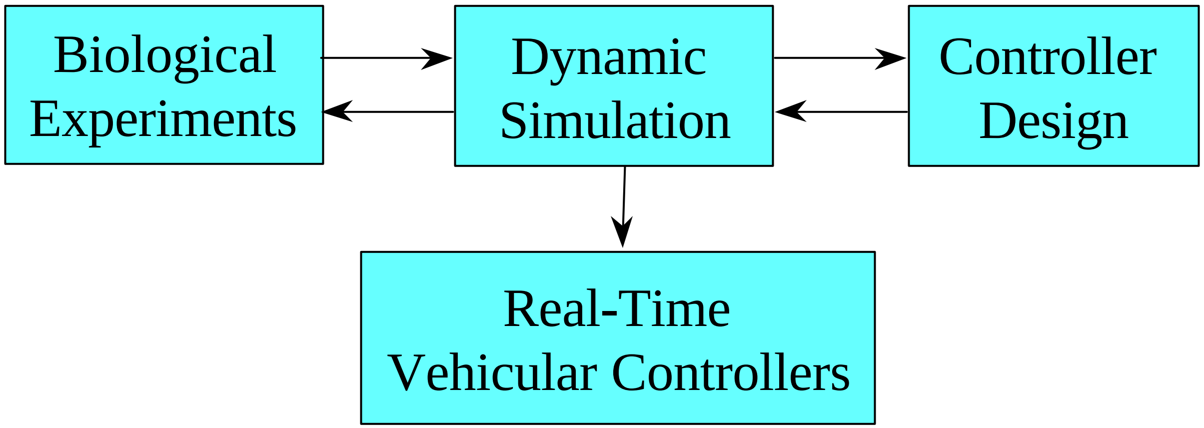
Enabling similar abilities to autonomous munitions would greatly enhance their utility and performance

Biologically-Inspired Control

Project Synopsis :



Objective and Approach:



Technical Challenges:

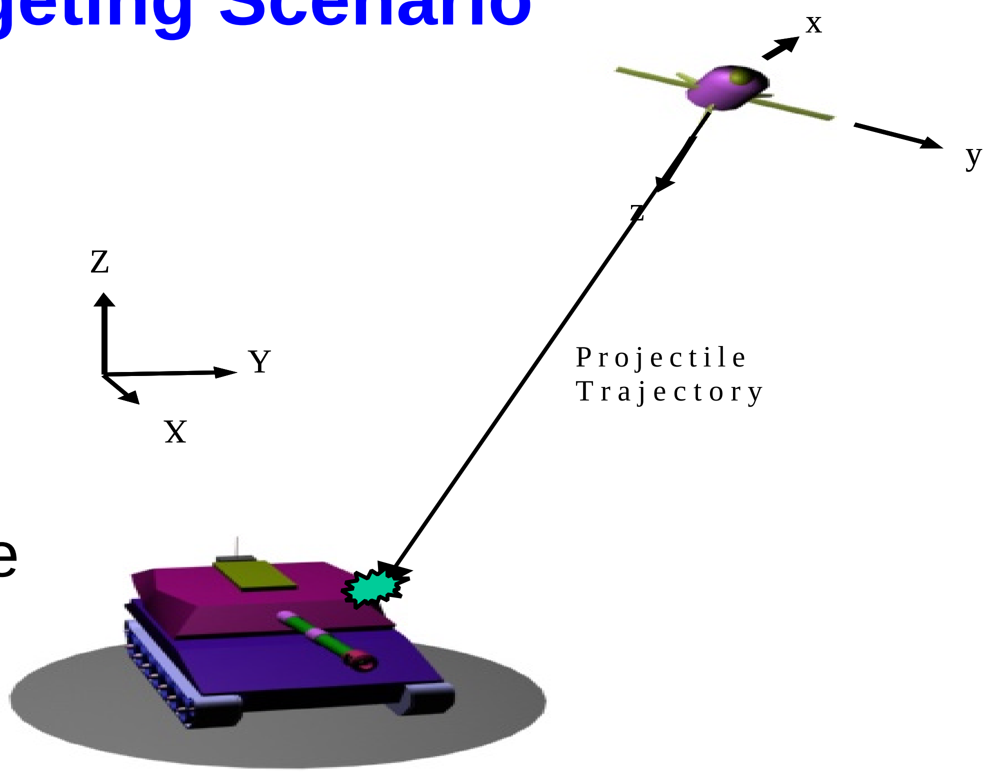
1)Extract salient features of animal behavior

2)Implement them as workable systems in mobile vehicles

Results to date:

- Insect-based distributed control for terrain locomotion
- Construction of 3 generations of cockroach-like robots
- *BioAVERT* neural circuit mapping the cockroach reflexive escape response developed for instantaneous vehicle escape
- BioSeek reflex developed for air vehicle targeting
- Emergent behavior algorithms constructed for multi-agent coordination
- Biology provides inspiration to solve engineering problems

Focus 1: Loitering Munitions with Air-to Ground Targeting Scenario



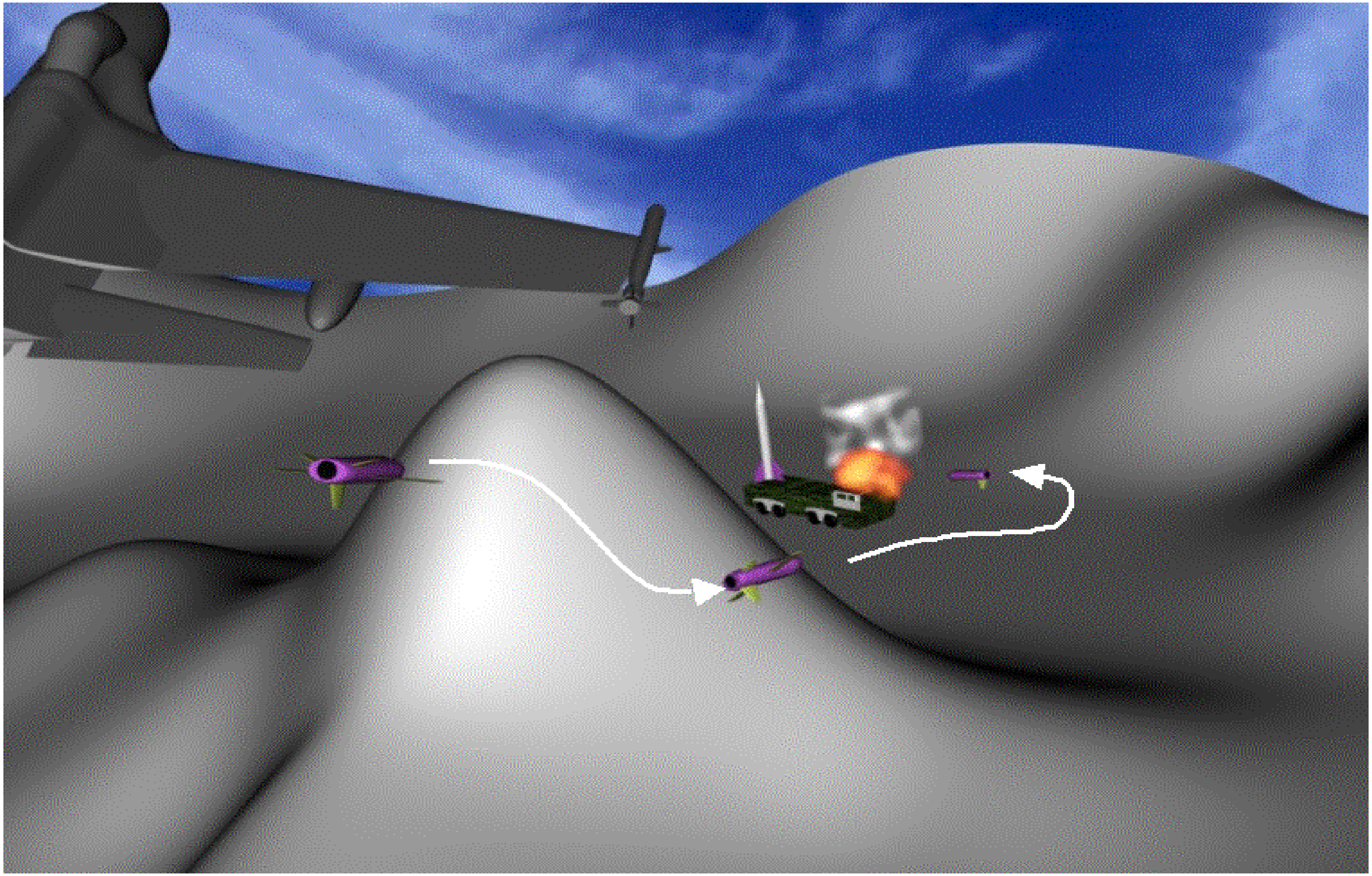
Goal-Seeking Scenario:

Generate control inputs piloting the munition to a point insuring target strike for unique air vehicle platform

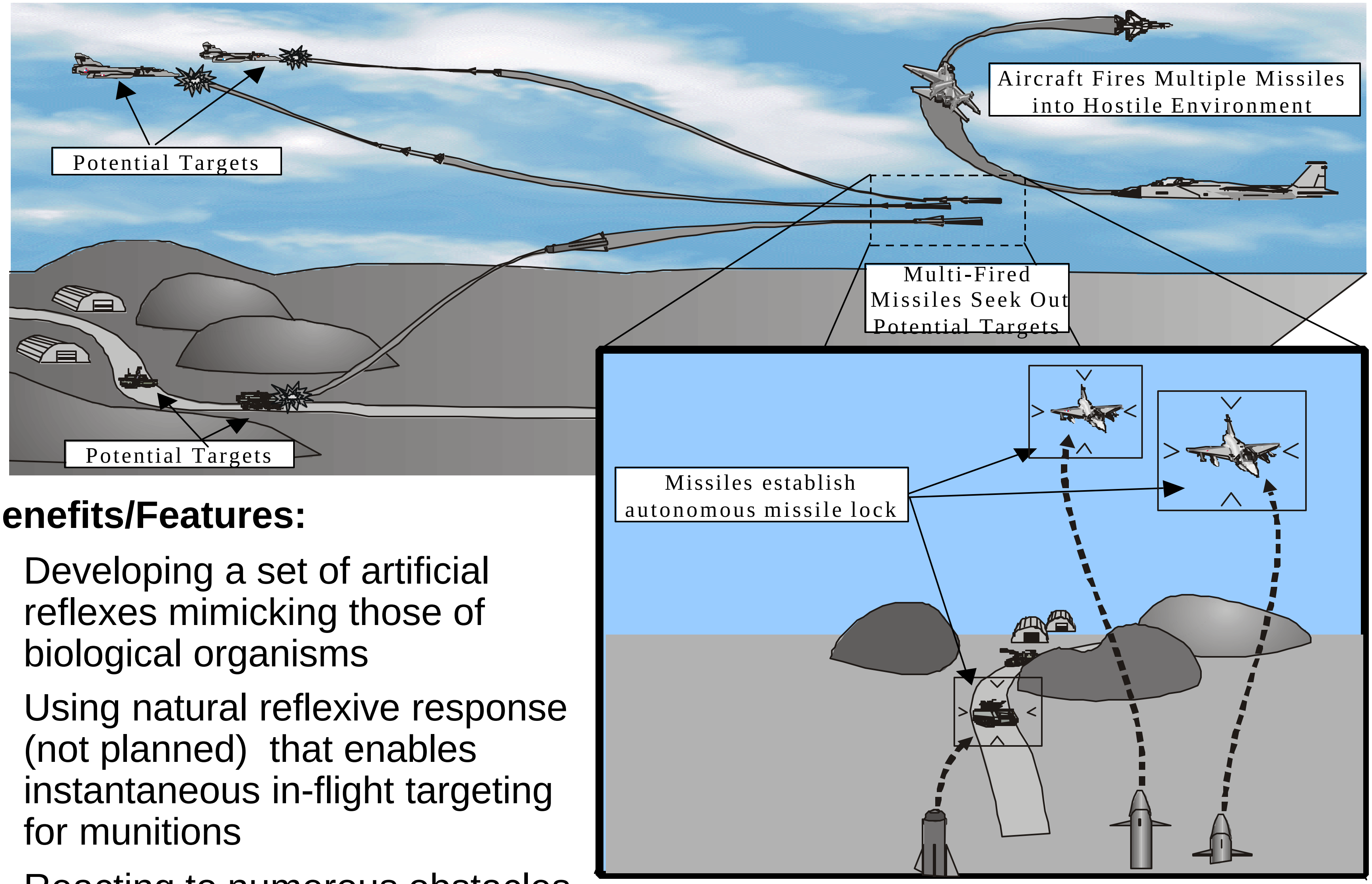
Application of Biologically Inspired Reflexes

- Flexible Endgame Reflex to Control Air Vehicle in the Presence of Unexpected Disturbances to Ensure High Probability of Kill per Shot
  - Targeting reflex provides high degree of accuracy required for unitary warhead
  - Targeting reflex counters and adapts to unexpected environmental upsets such as updrafts and cross-winds that can significantly impact lightweight air vehicles
- Collision Avoidance Reflex to Prevent Unexpected Controlled Flight Into Terrain or Other Air Vehicles
  - Collision avoidance reflex will endow the air vehicle the ability to autonomously avoid unexpected collisions and continue its mission even in the presence of rugged terrain or urban environments

Focus 2: Endgame Enhancement of Vehicles Maneuvering Away from Collision BUT still Maintain Path to hit Target



BIOSEEK - Biologically Inspired Target Seeking Reflex for Autonomous Munitions/Neural Network

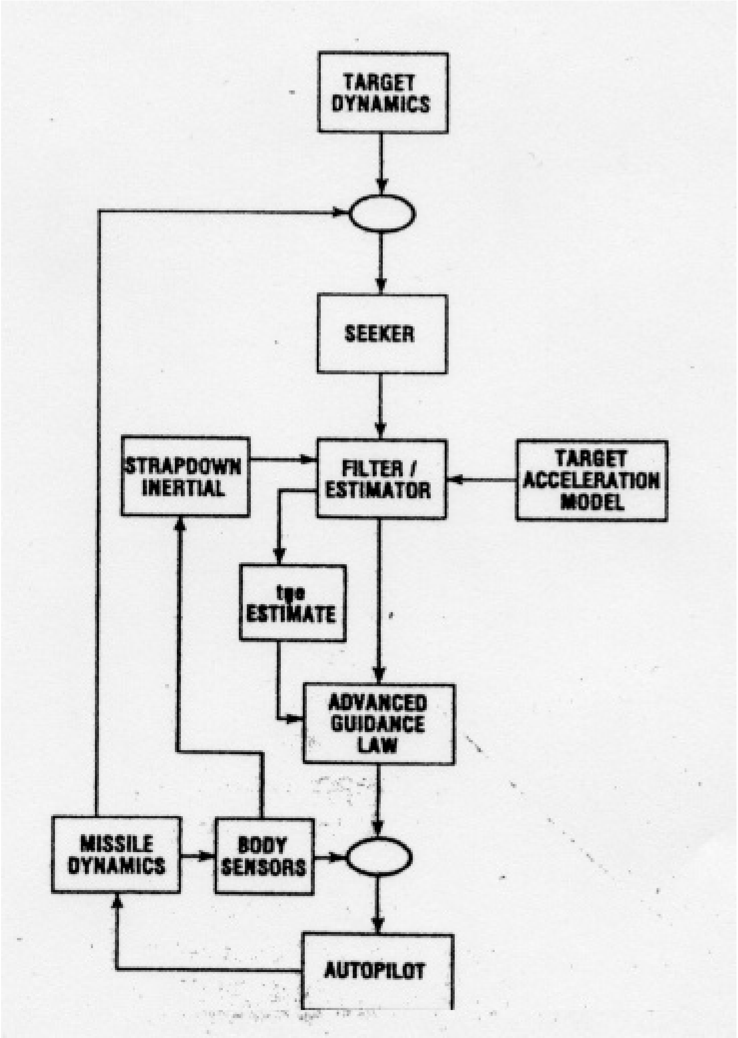


Benefits/Features:

- Developing a set of artificial reflexes mimicking those of biological organisms
- Using natural reflexive response (not planned) that enables instantaneous in-flight targeting for munitions
- Reacting to numerous obstacles while maneuvering within vehicles constraints (flight envelope)

Autonomous Munition Guidance

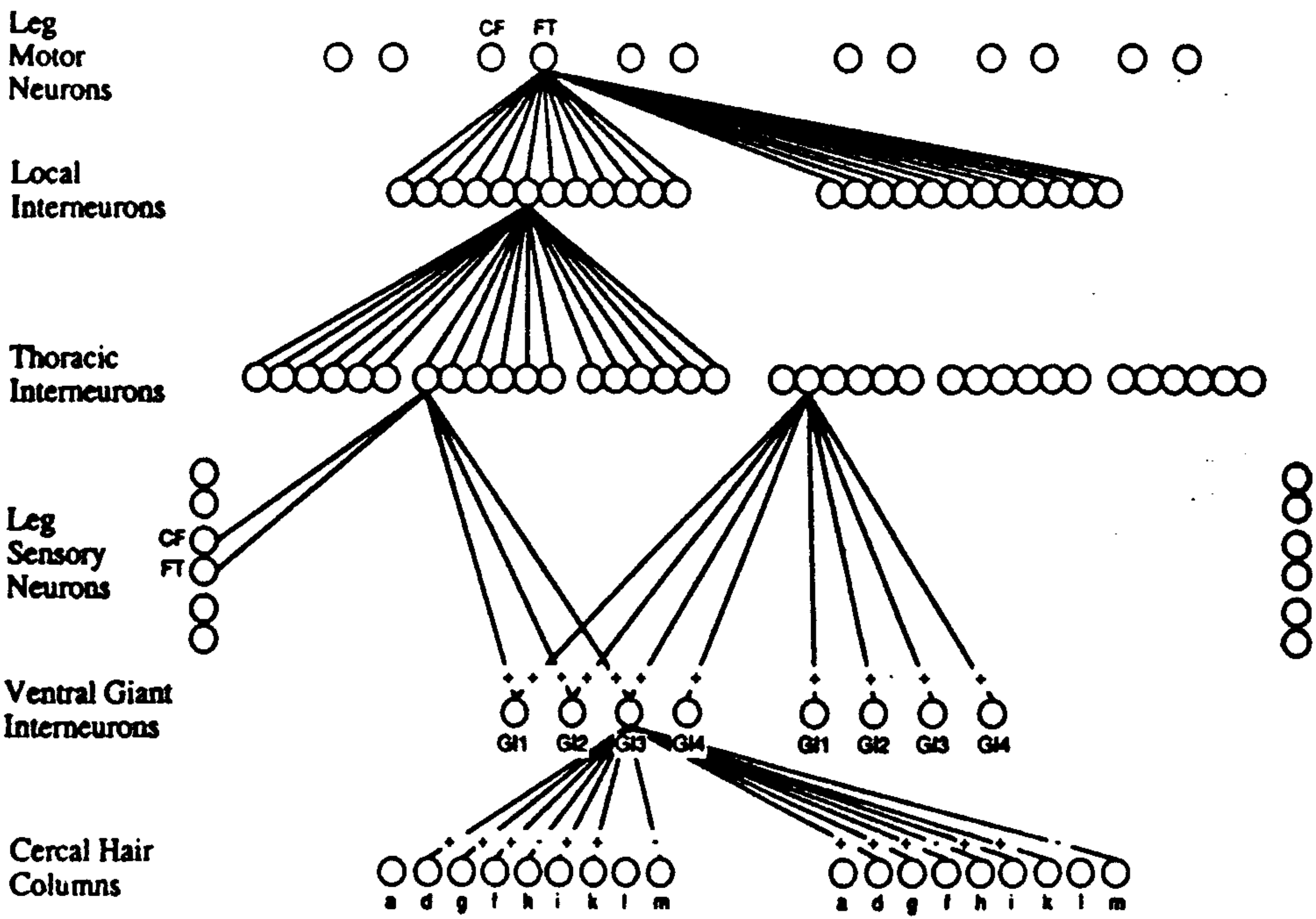
- Problem consists of:
  - Estimations of target motion
  - Generation of guidance commands
  - Control of munition
- Estimation filter processes target information obtained from seeker
- Guidance law produces command rates
- Autopilot converts input to thrust and control surface commands
- The resulting motion closes the feedback loops
- Focus on Guidance Law Development



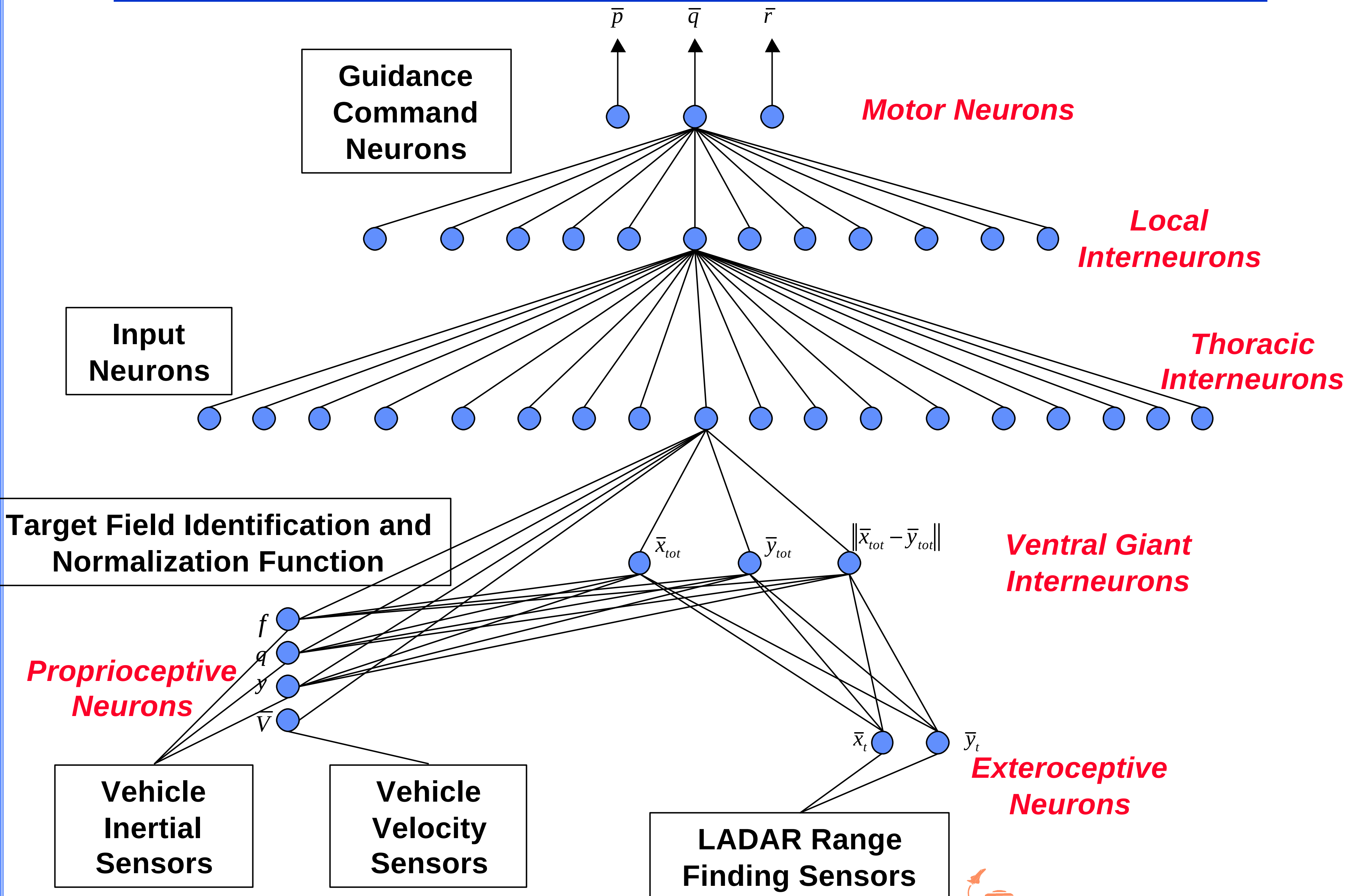
FCS Block Diagram [Cloutier, 1989]

Review of:
Neural Nets and Genetic Algorithms

Model of Cockroach Neural Network



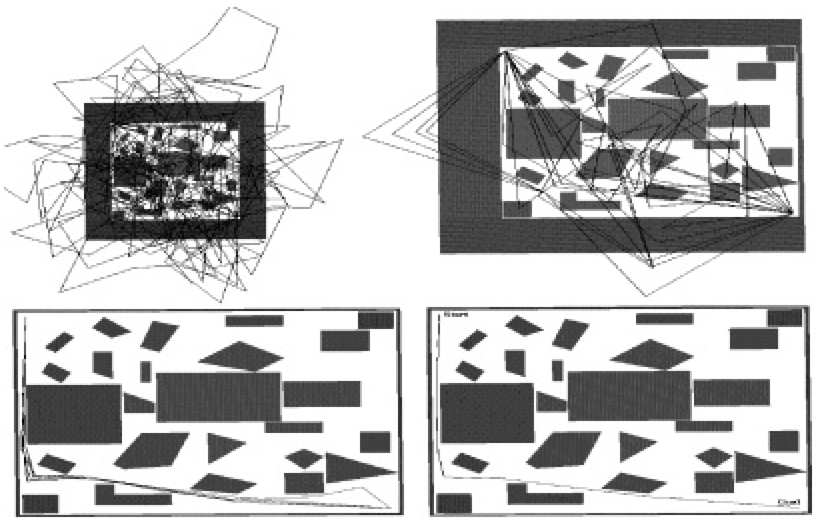
Guidance Reflex for Autonomous Munitions



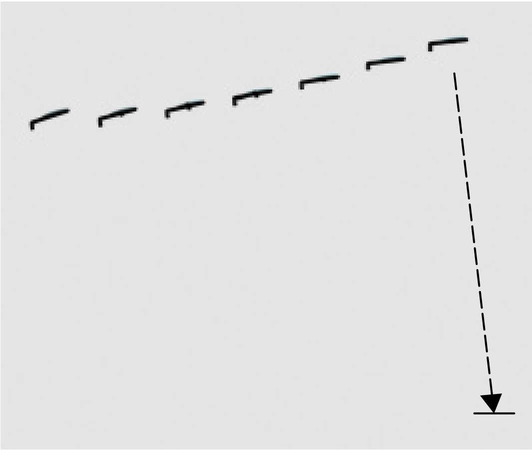
Target-Seeking Reflex Learning

- **Sufficient data is needed to train the system**
- **A path-planning scheme is developed to create training trajectories**
- **Trajectories are used to train the neural network such that they may be reproduced instantly to track targets**

MAPPER/Genetic Algorithm



MAPPER Path Generation Process for a Point Robot in an Obstacle Ridden Environment



Benefits/Features:

- Genetic (evolutionary) algorithm evolves searching pattern to find best path for autonomous vehicles
- Computational efficiency proven for 6 degrees of freedom in 3-dimensional scenarios
- Proven to find “best” possible path quickly for complex vehicles with maneuvering limitations

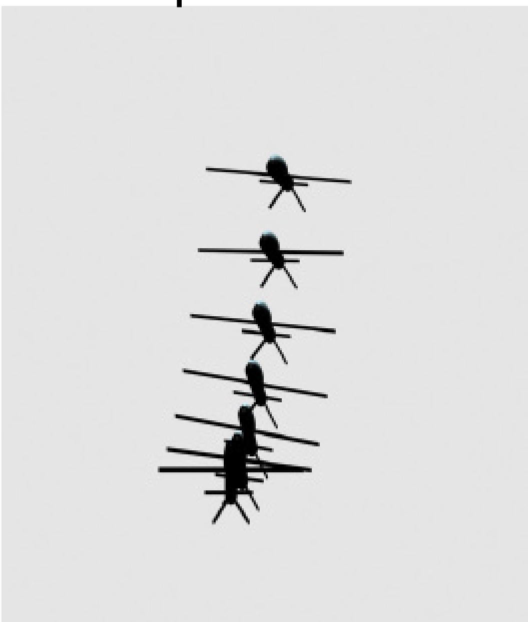
- Generates inputs to fly air vehicle to a point where a projectile would strike near center of target
  - Flight constraints
  - Path destination
  - Final Orientation
- Feasible Path to Target found within 100 generations
- Optimized off line to improve hit near center of Target

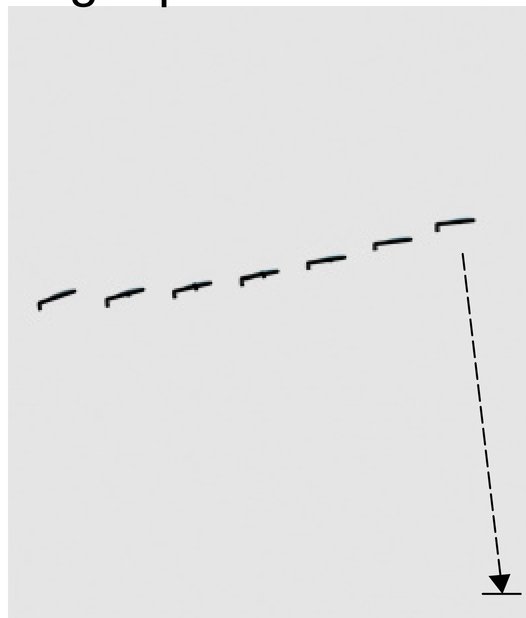
Evolutionary Targeting

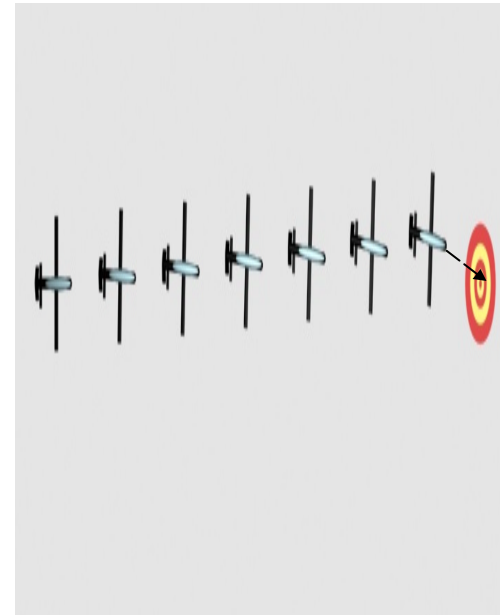
IC: Initial AoA, sideslip, pitch, 2.5m rad. **target 30m x, 0m y**

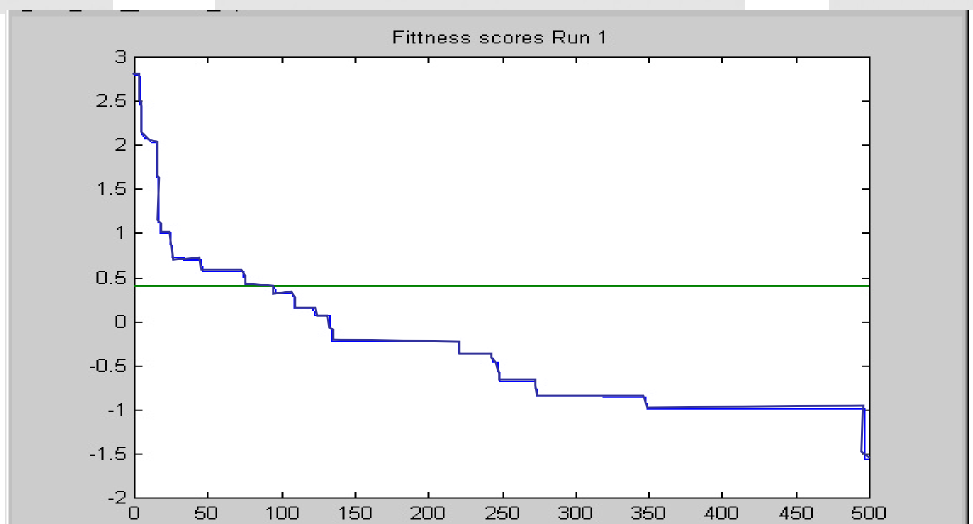
Evolutionary Evaluation: 500 Generations, Target acquired @100

Output: 0.59 sec flight, target pt. 0.027m off center







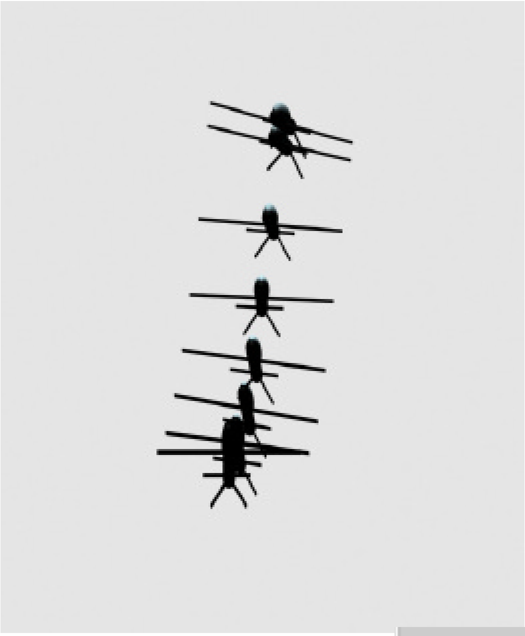


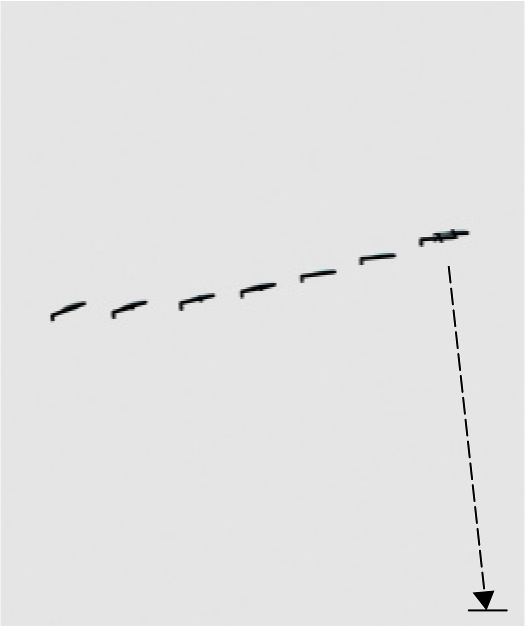
Evolutionary Targeting

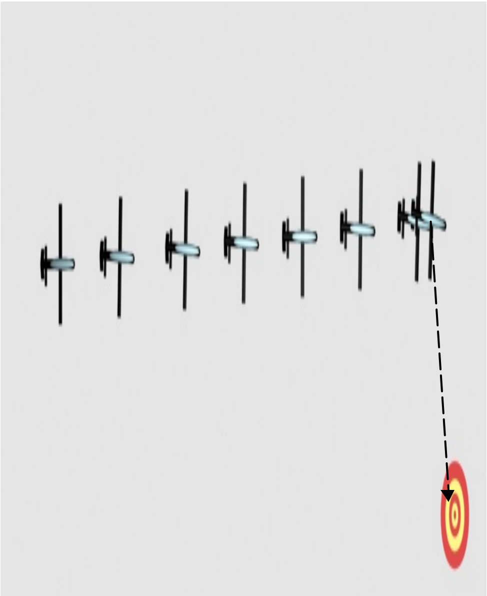
IC: Initial AoA, sideslip, pitch, 2.5m rad. **target 30m x, 5m y**

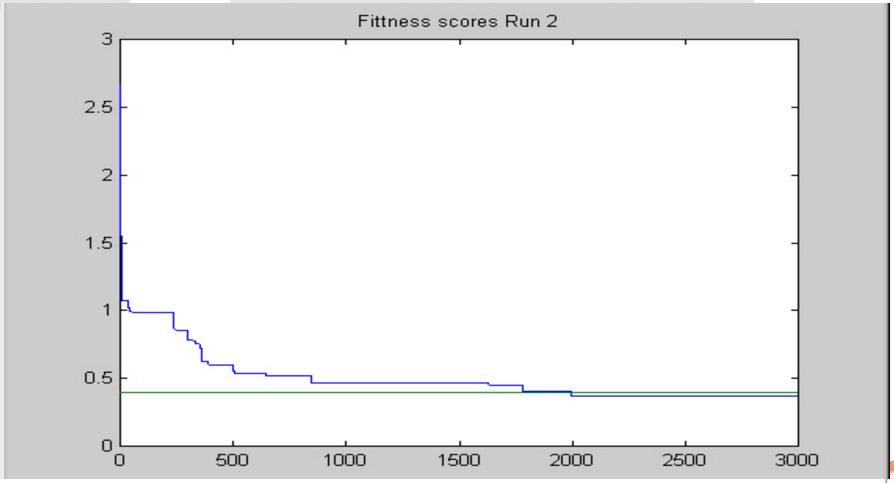
Evolutionary Evaluation: 3000 Generations, Target acquired @~2000

Output: 0.63 sec flight, target pt. 0.35m off center



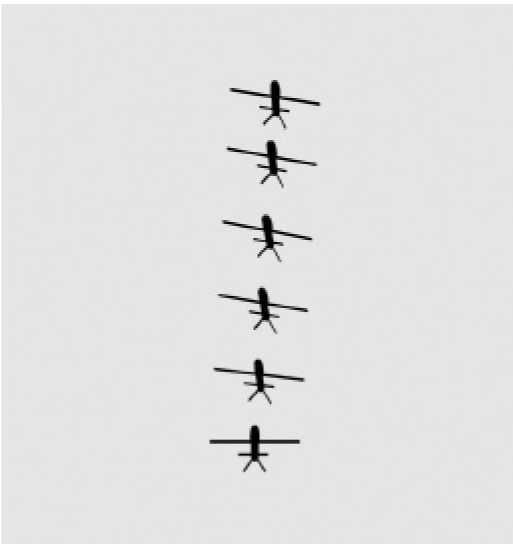


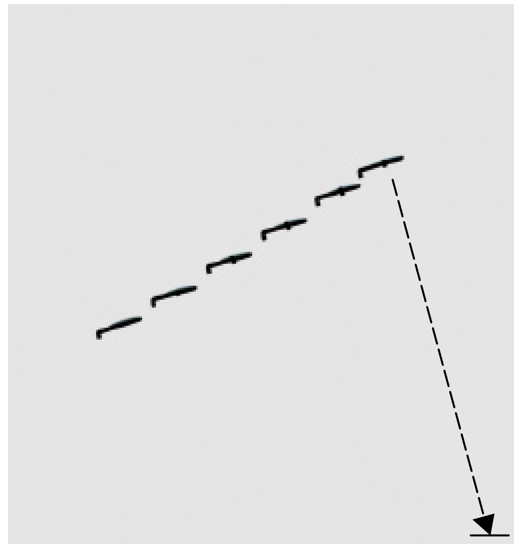


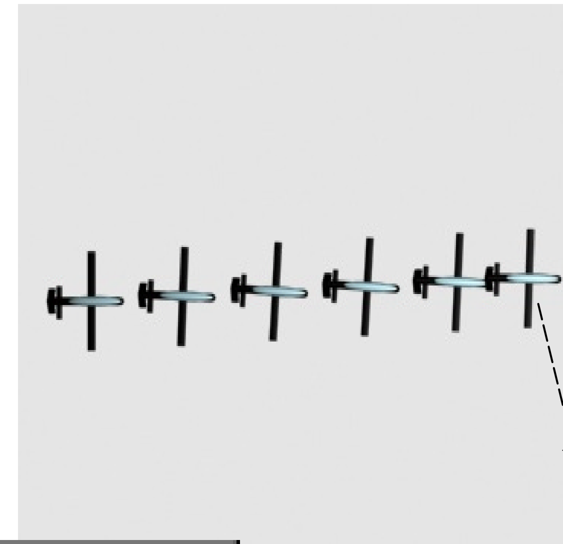


Evolutionary Targeting

IC: Initial AoA, sideslip, pitch, 2.5m rad. **target 30m x, -5m y**
Evolutionary Evaluation: 3000 Generations, Target acquired @~80
Output: 0.47 sec flight, target pt. 0.09m off center





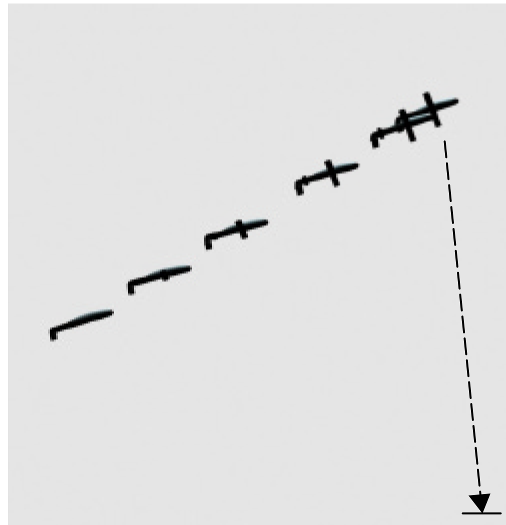


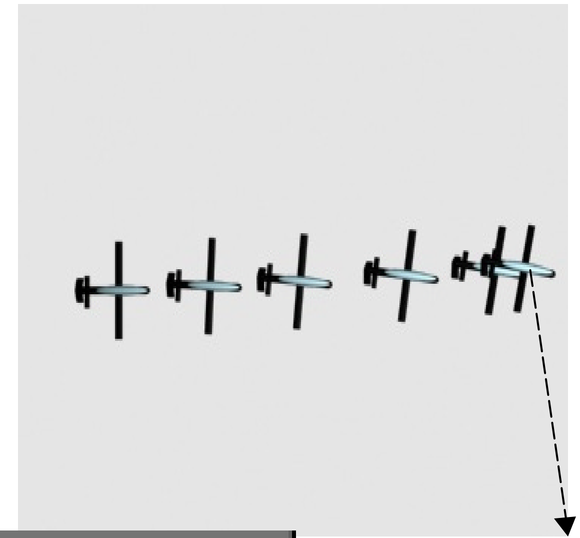
Evolutionary Targeting

IC: Initial AoA, sideslip, pitch, 2.5m rad. **target 30m x, 10m y**

Evolutionary Evaluation: 3000 Generations, Target acquired @~100

Output: 0.45 sec flight, target pt. 0.01m off center



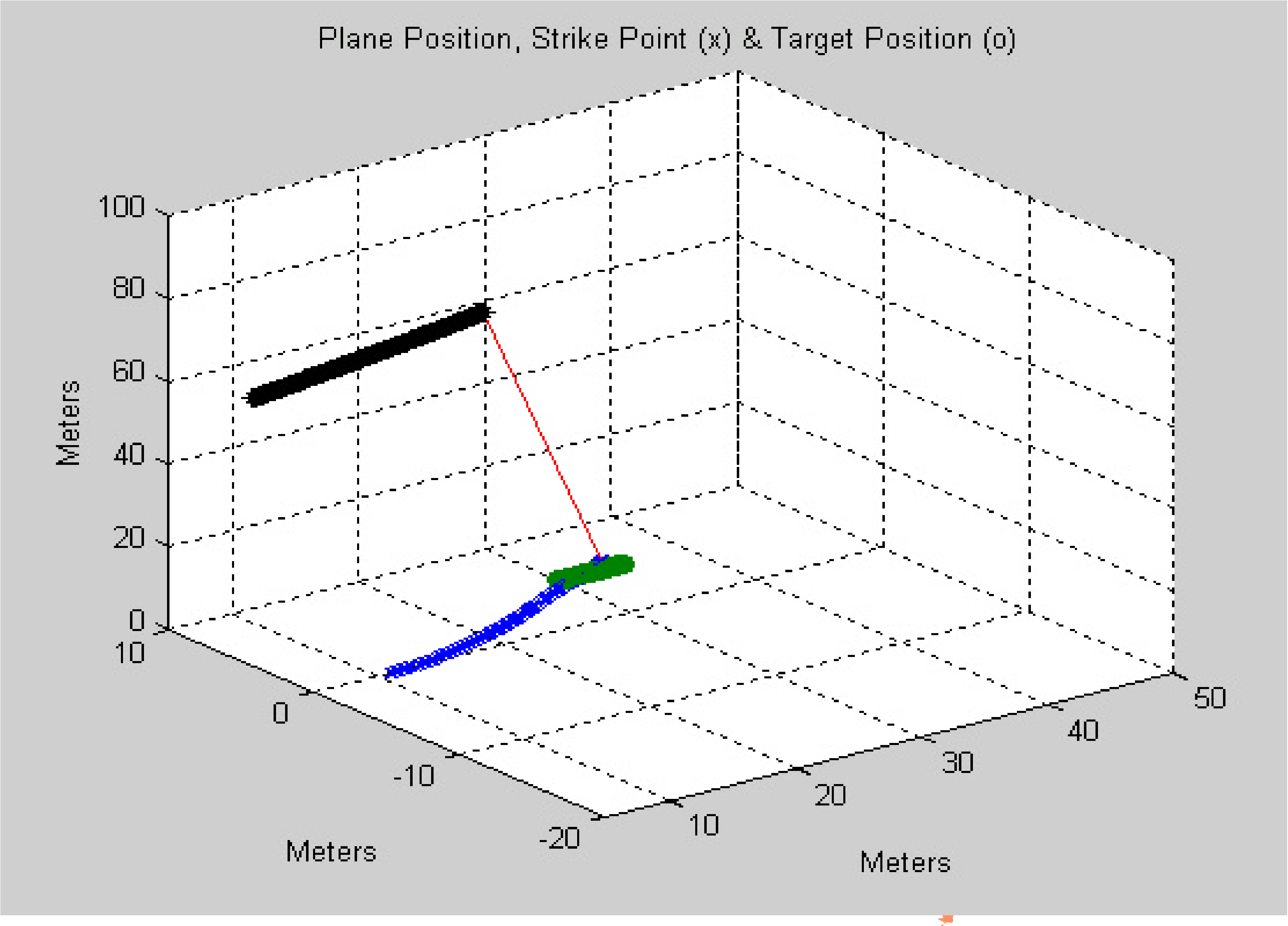


Untrained Targeting Situations

- Genetic Algorithms generated a set of inputs which would fly the munition to a point where a projectile would strike near center of target
- **Neural networks represent complex Genetic Algorithm data in compact structures for fast throughput.**
- **Neural Networks will select best Genetic Algorithm or will combine solutions**

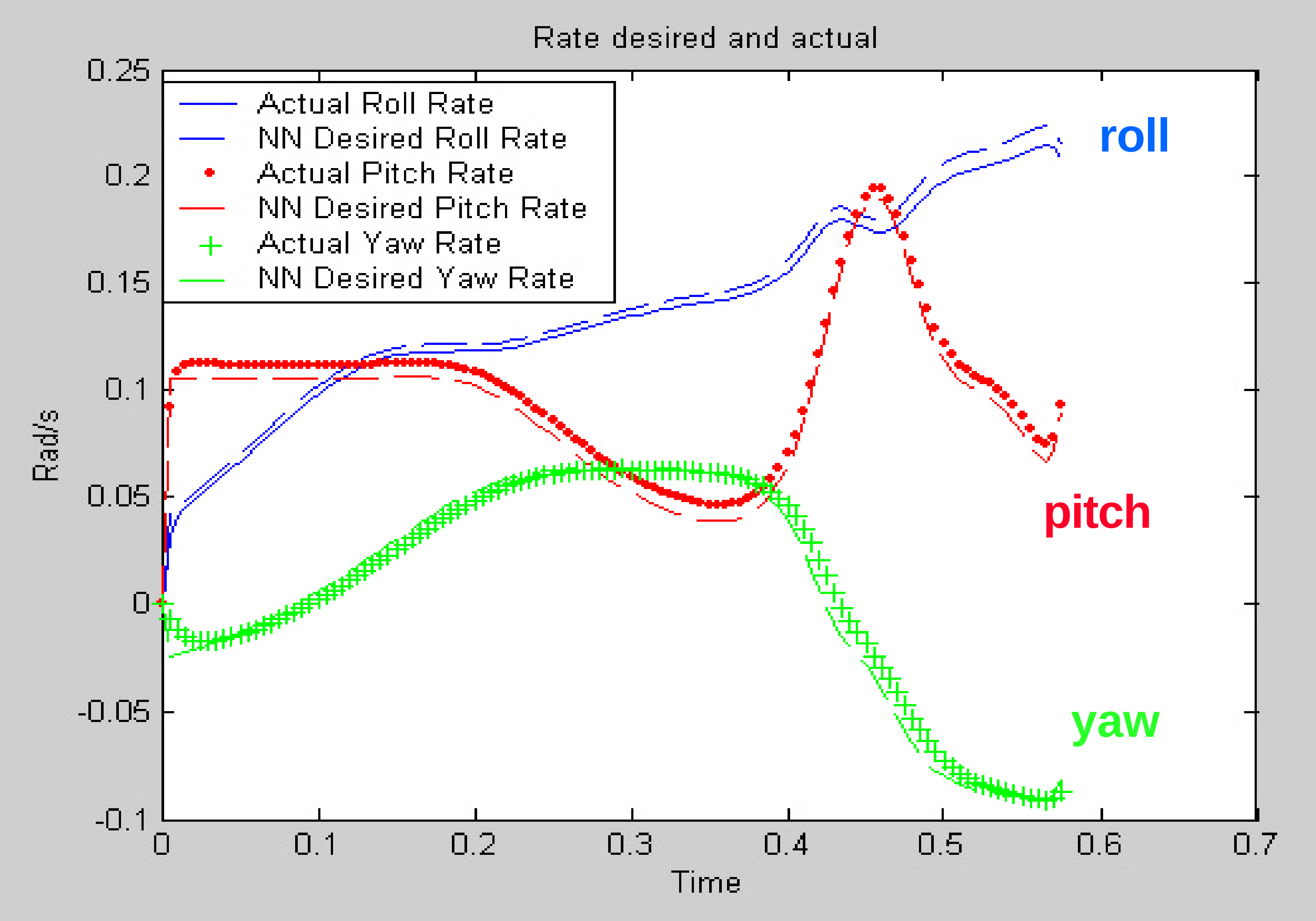
Mobile Targets

- Common end game operational scenario for “Tail Chase”
- Acquired Target 30 m in front, 5 m left moving at 10m/s (35% AV Speed)



Mobile Targets (moving one direction)

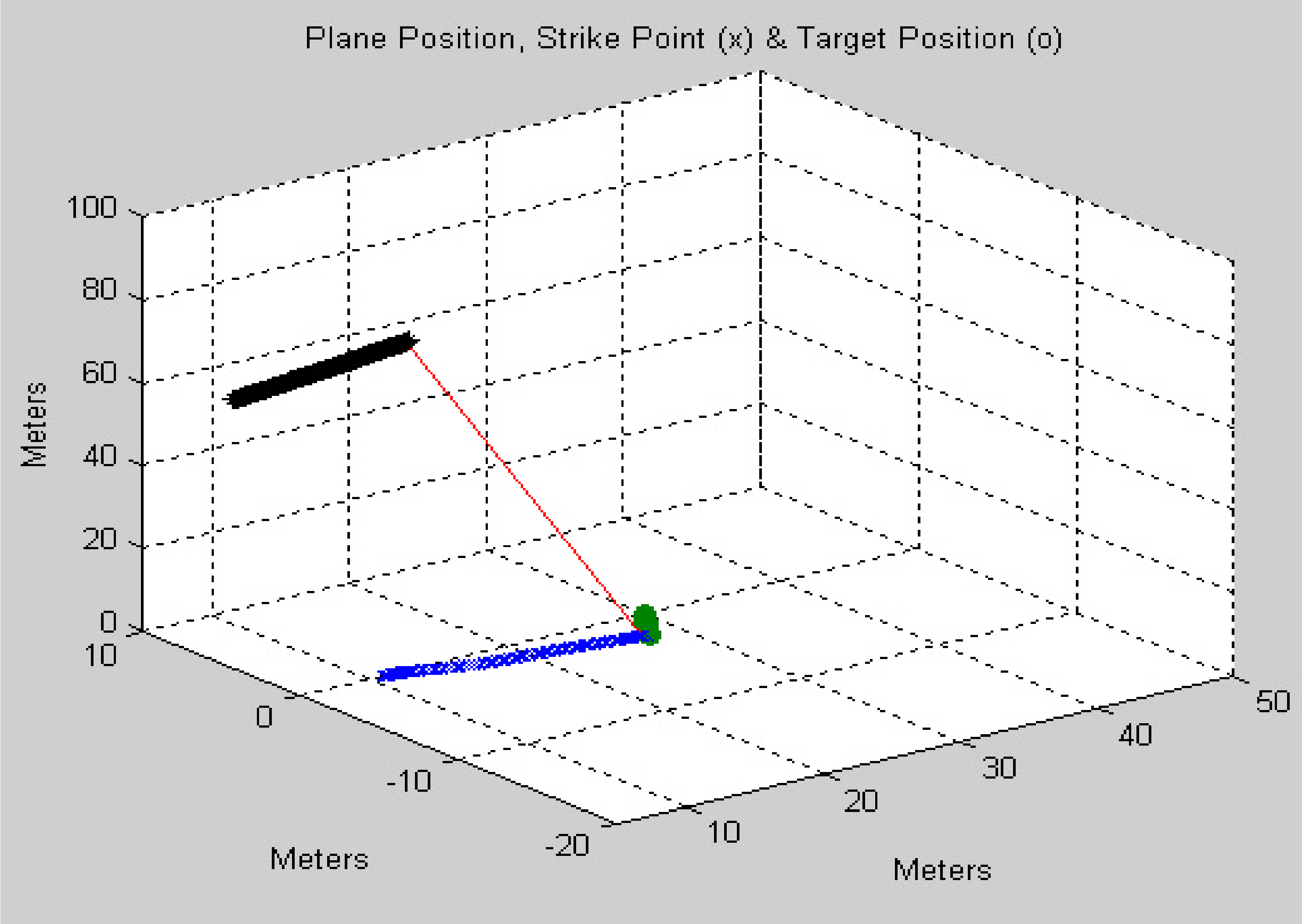
- **Common operational scenario for "Tail Chase" - Target begins 30 m in front, 5 m left moving at 10m/s (35% AV Speed)**
- **Algorithm determines the ideal roll, pitch and yaw rates to hit target**



Within Vehicle Constraints

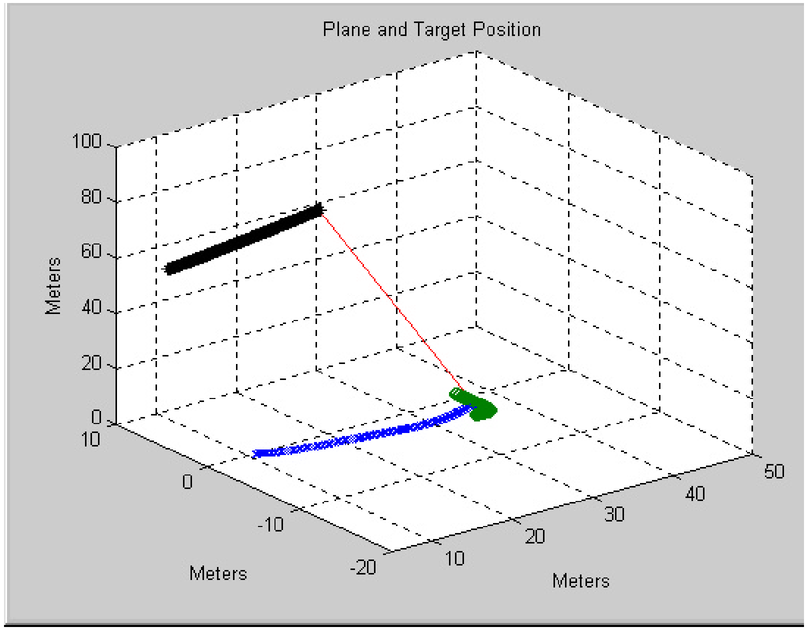
Mobile Targets – Random movement (0.2 sec)

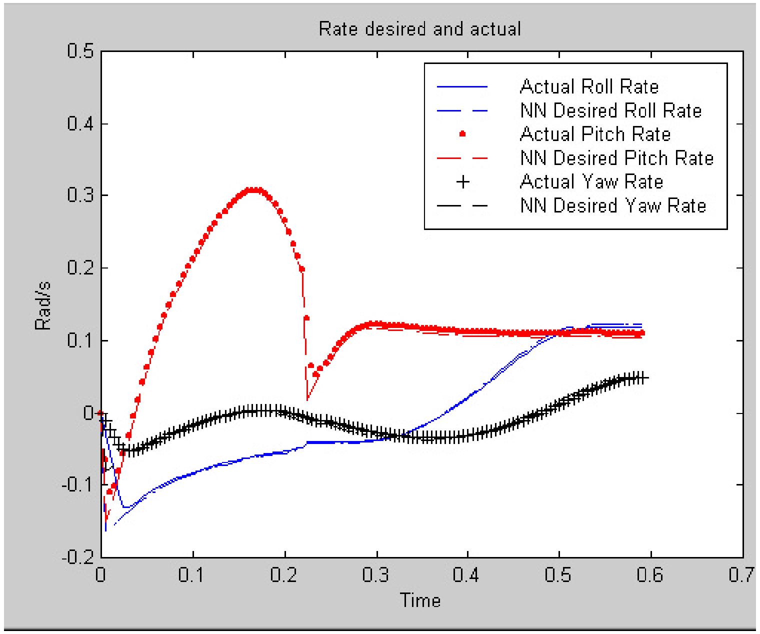
- Common "Tail Chase" Scenario
- Dynamic target starting 30m in front of the air vehicle, moving in different directions at 10m/s; reflex adapts in each case (over 10,000 scenarios tested)
- Reflex shows 83% Confidence Ratio for targets moving at 40% of AV speed



Evading Targets (Moving then Changes Direction)

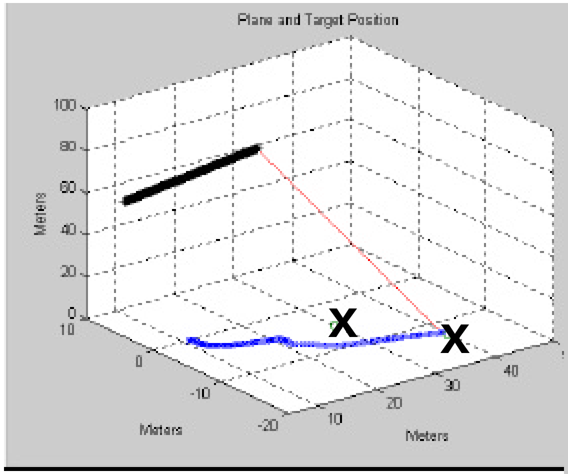
- Target may make abrupt random changes in its path
- Target 35 m in front 5 m to right w/initial 10m/s forward. At 0.2 sec. turns 90°
- Strike distance 1.2 m
- 79% Confidence Ratio for targets turning randomly with speed up to 40% of AV

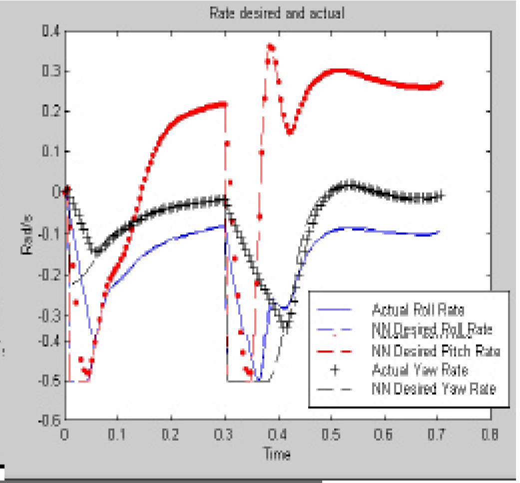


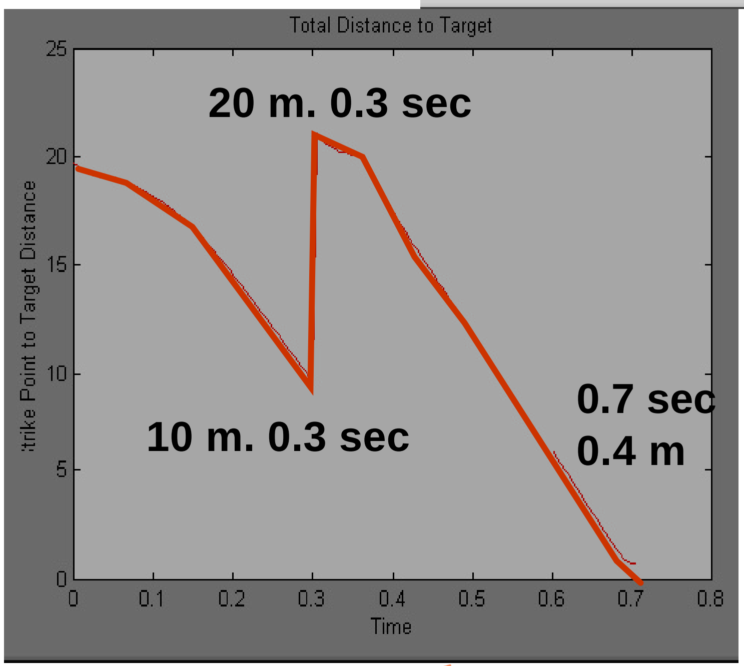


Reflex Performance with Sensor Data Interruption

- Target may possess sensor jamming capabilities or circumstances may cause sensor “blind spots”
- Target located 35 m in front, 5m to right of AV
- Target “jumps” 10m forward, 8m laterally (@ 0.3 sec)
- Targeting reflex instantly reorients munition and strikes target 0.4 m off center
- 67% Confidence Ratio for disruptions up to 15 m in front, +/- 7.5 m to left or right

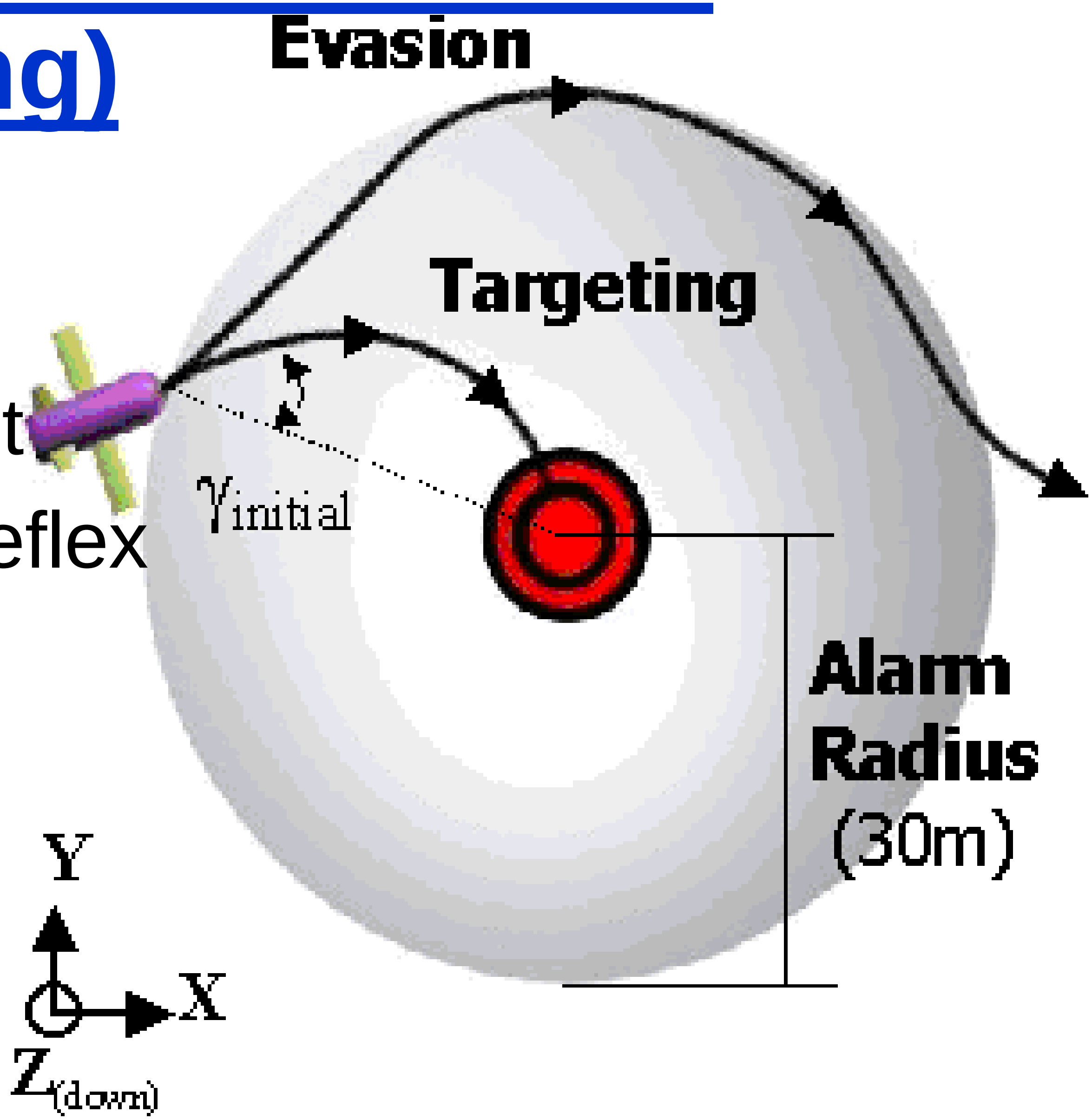






Flight Test of Reflexes (Targeting)

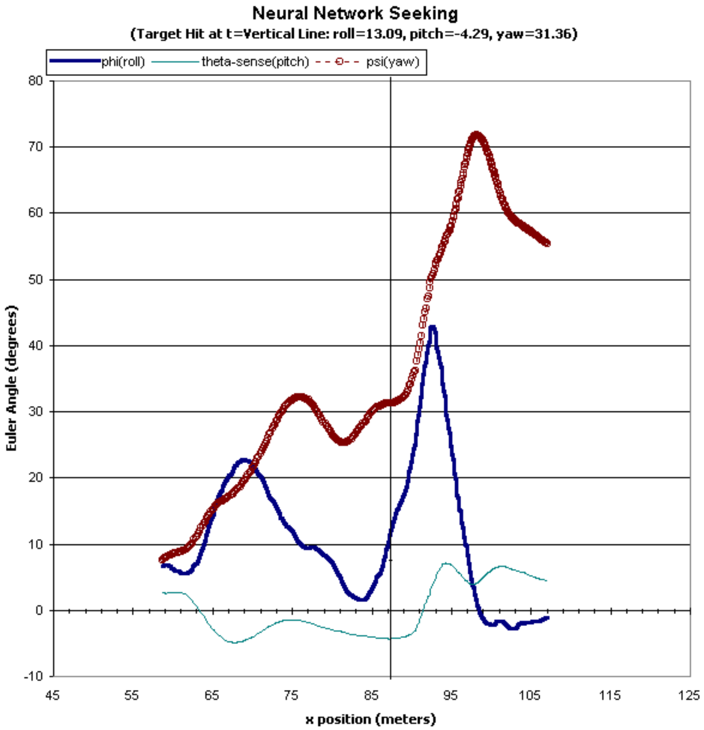
- Level Flight
- Evasion Reflex
- Targeting

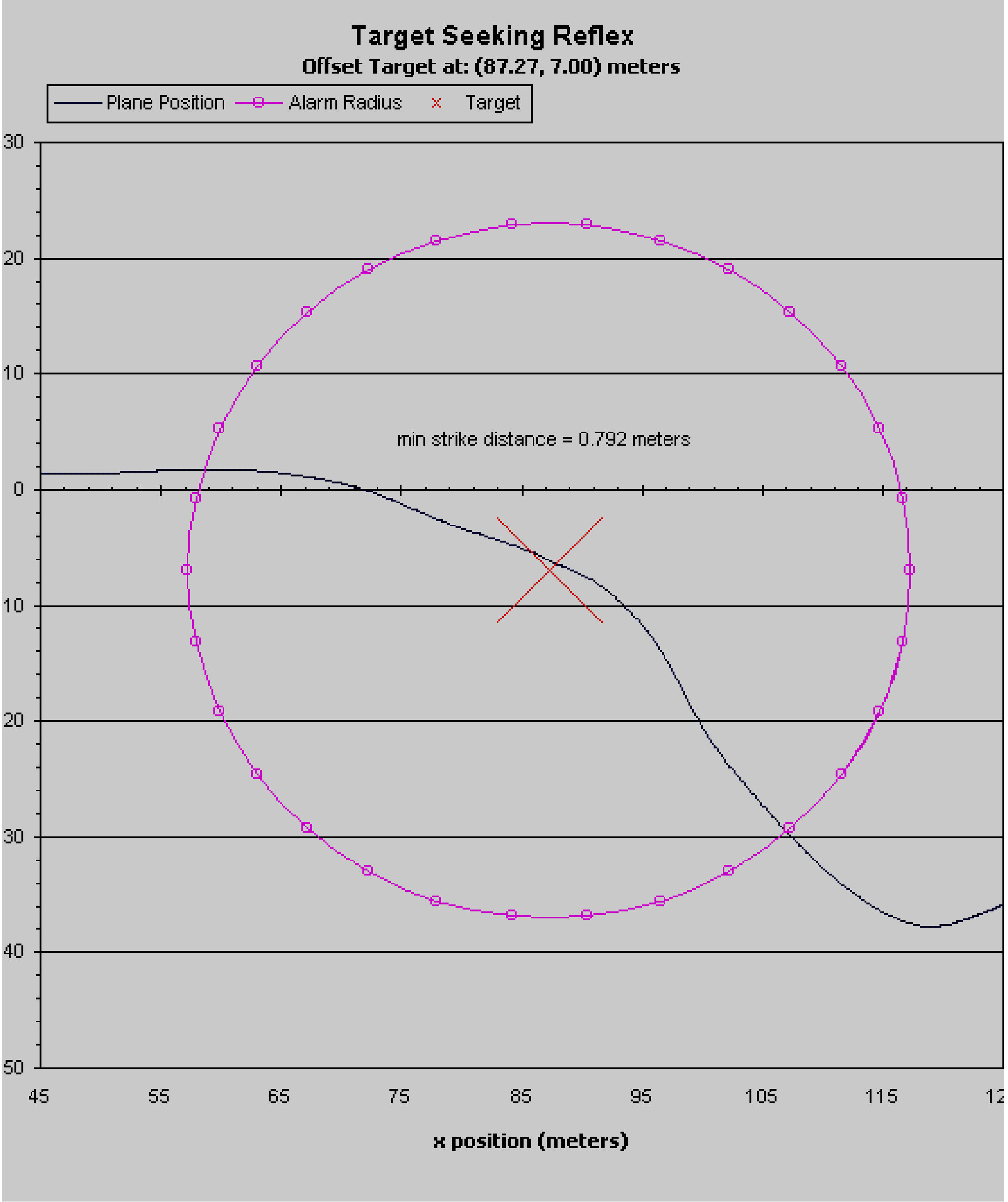


Hardware Platform

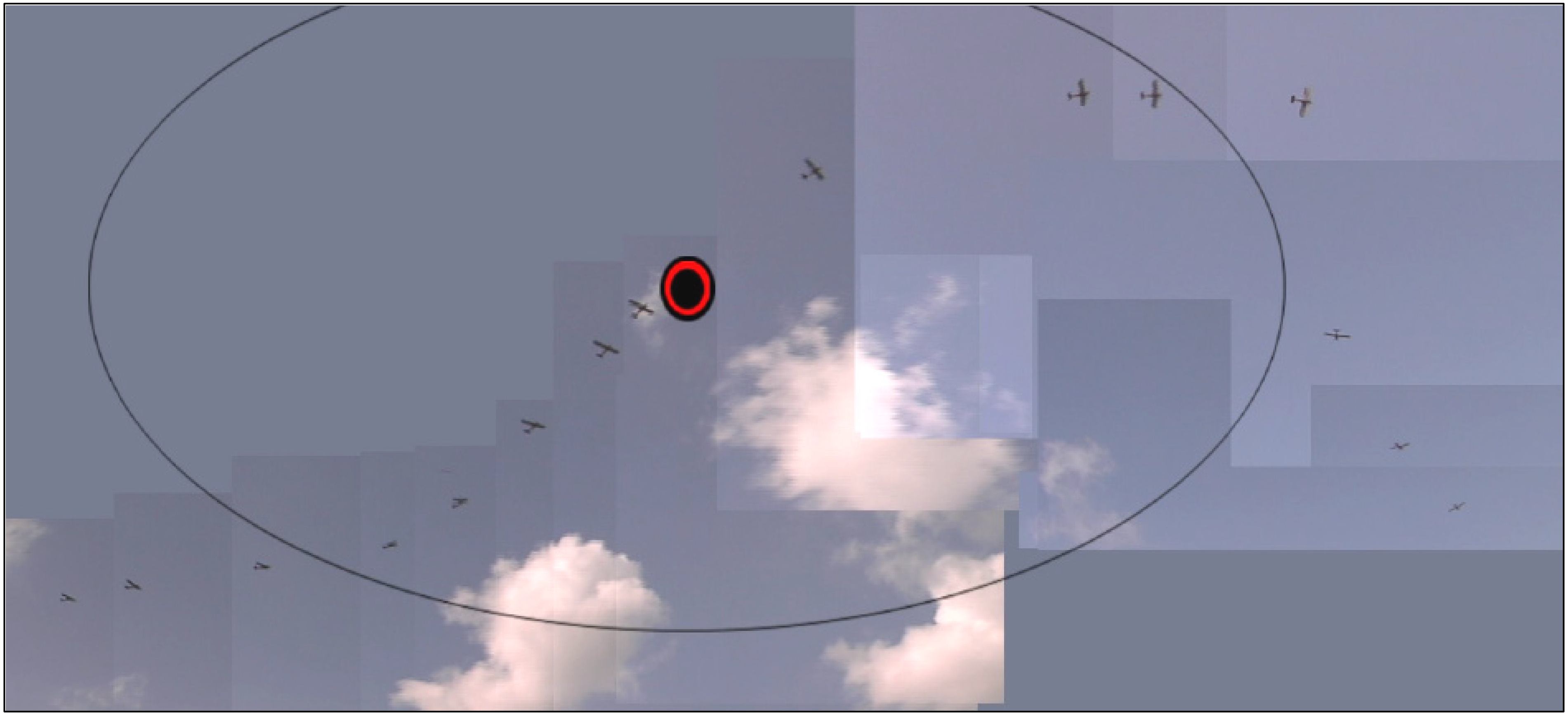
Type:	1/4-scale monoplane	Wingspan:	108 in.
Wing Area:	1,610 sq. in.	Length:	68 in.
Final Weight:	25 lb.		
Power Used:	Quadra 35cc	Prop Used:	Zinger 20 x 8

Seeking Example 1

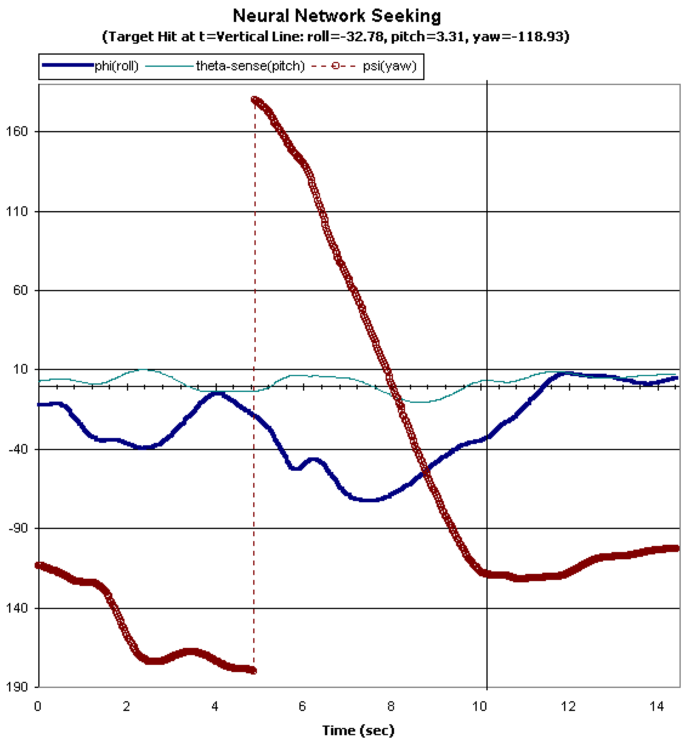


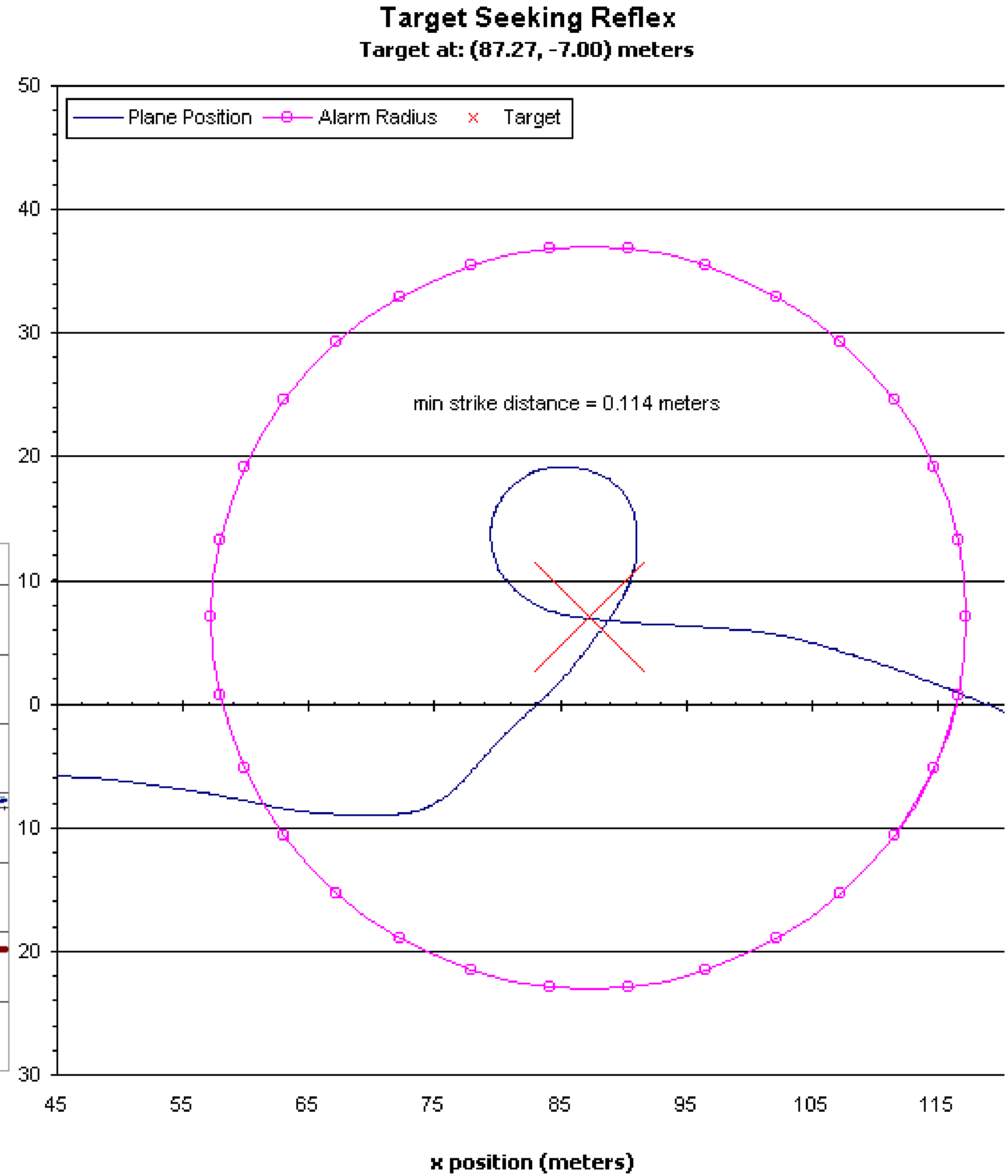


Composite Image from video showing an air vehicle striking a target

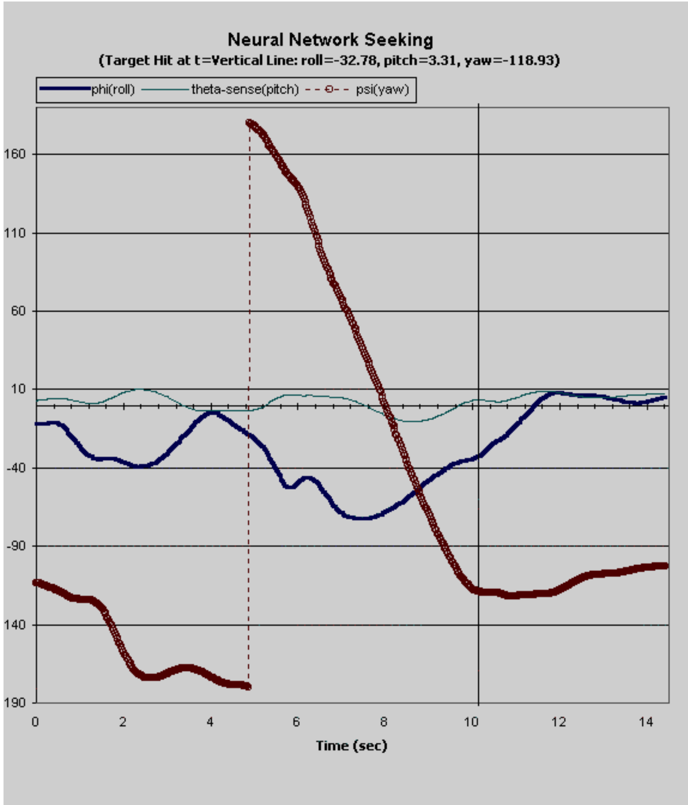


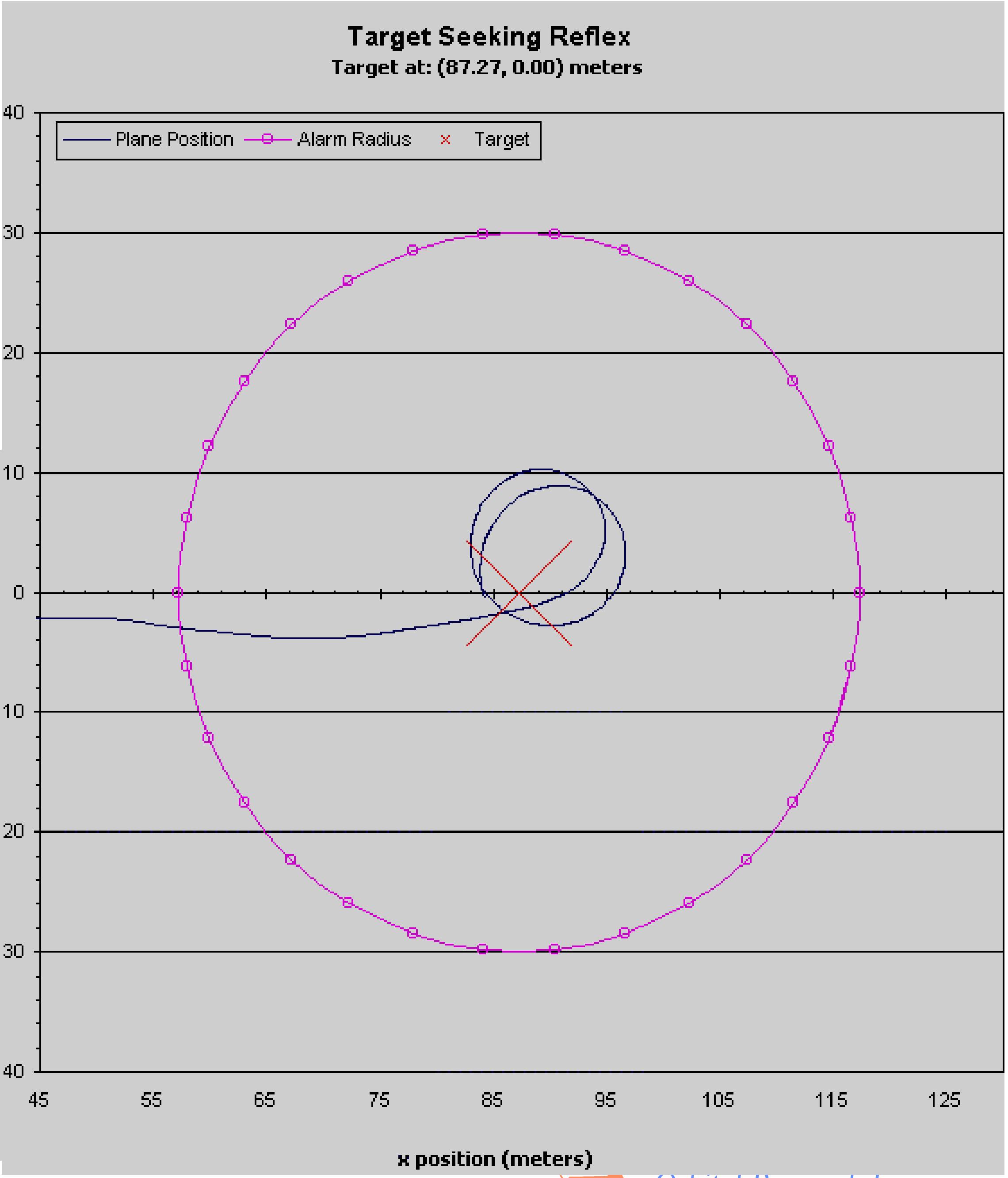
Seeking Example 2





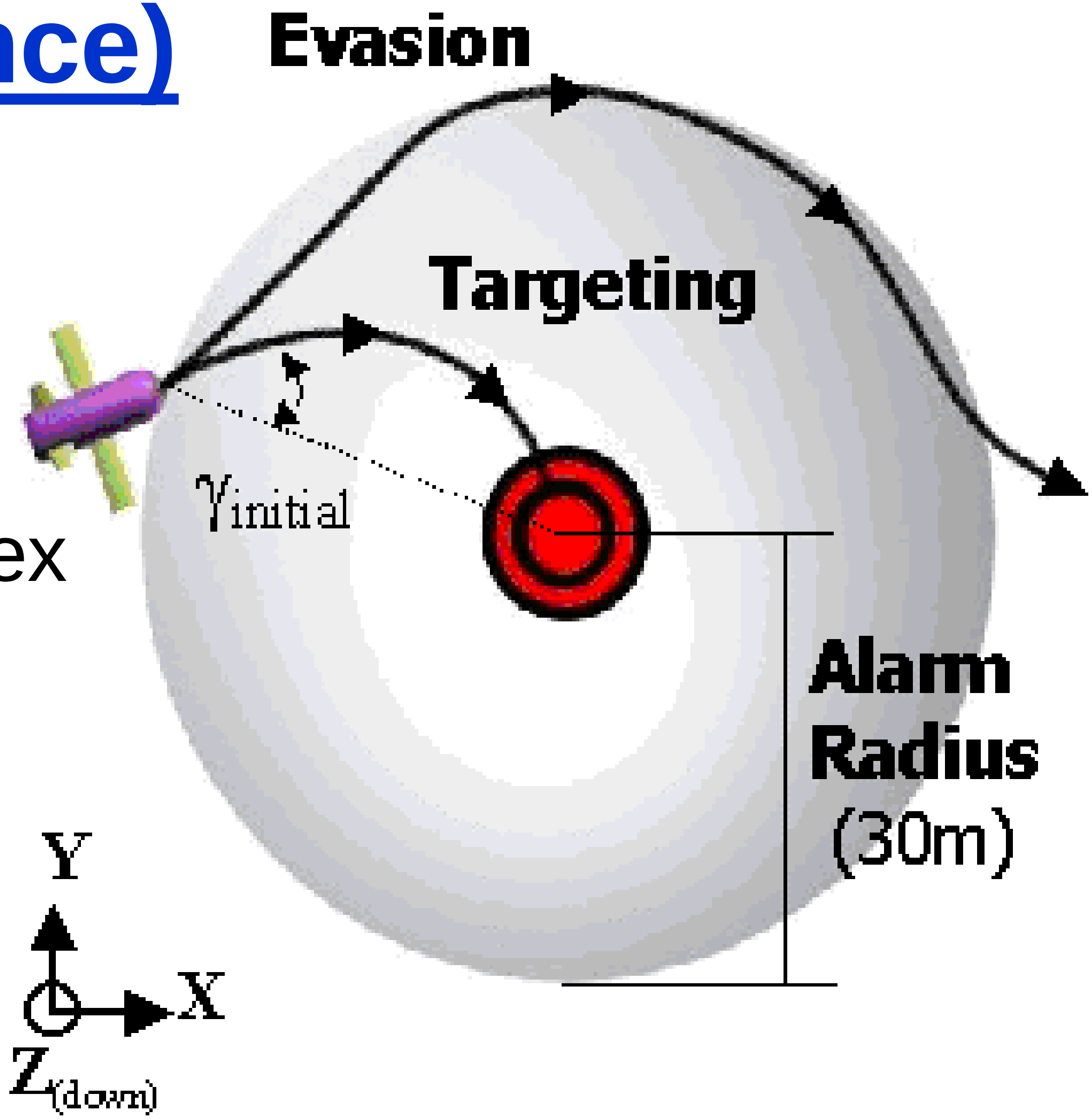
Seeking Example 3



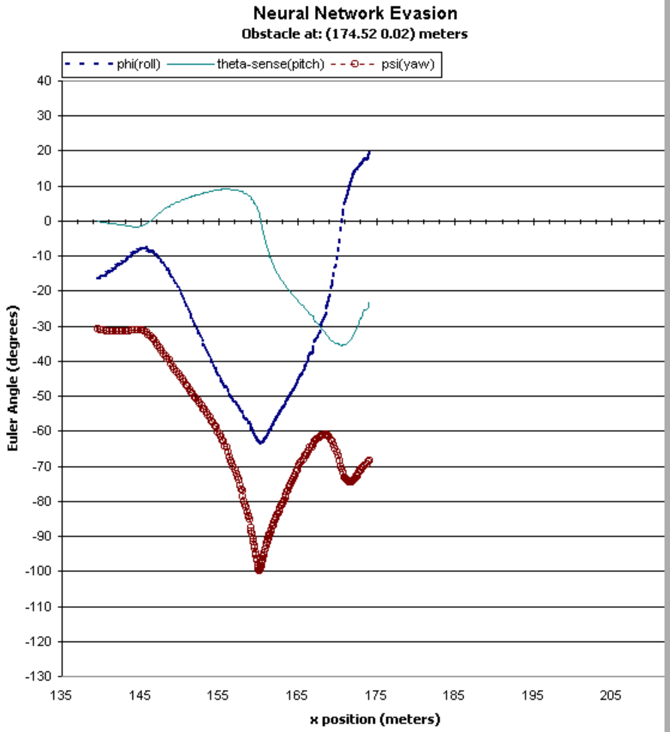


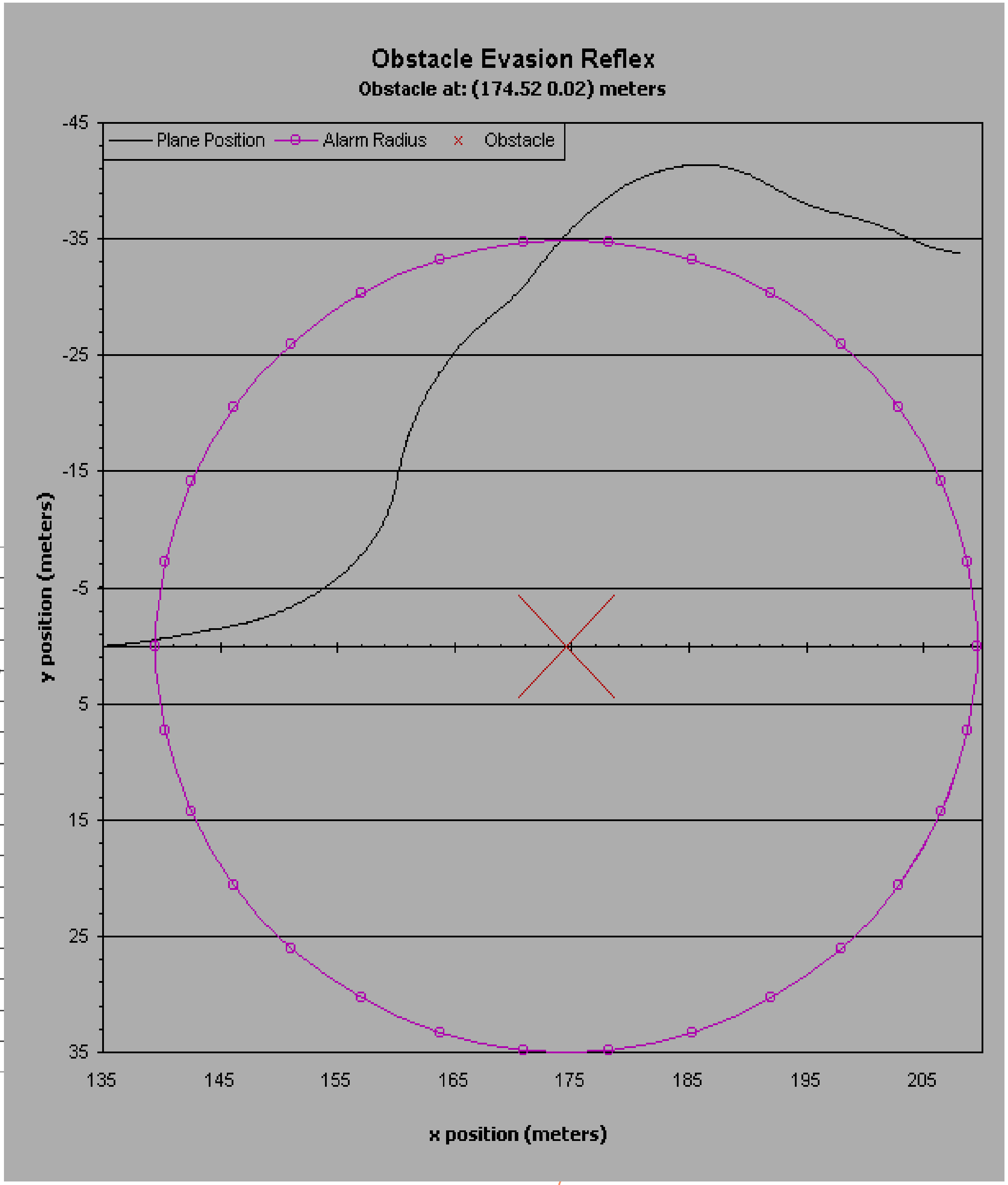
Flight Test of Reflexes (Avoidance)

- Level Flight
- Evasion Reflex
- Targeting

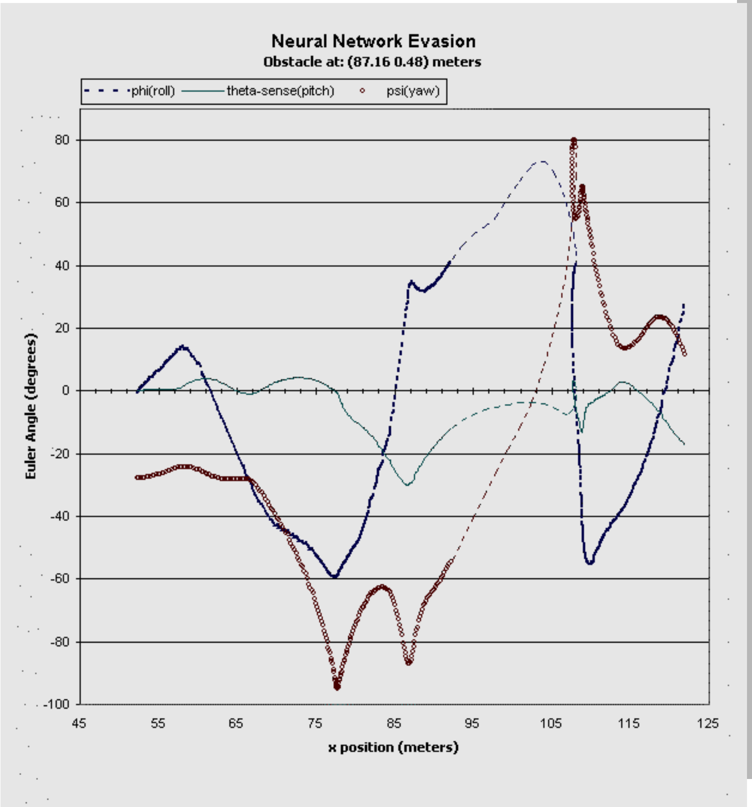


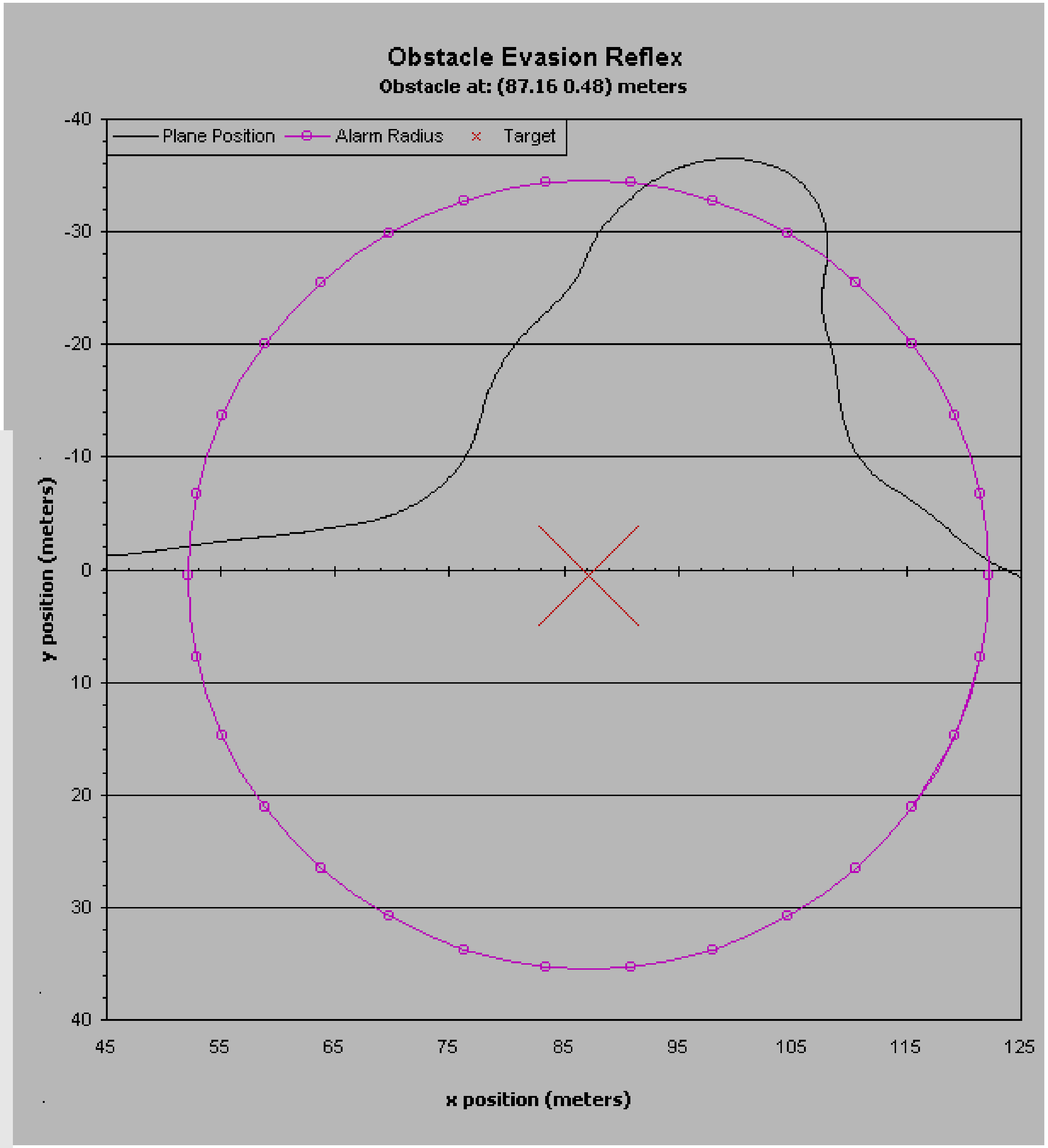
Evasion Example 1



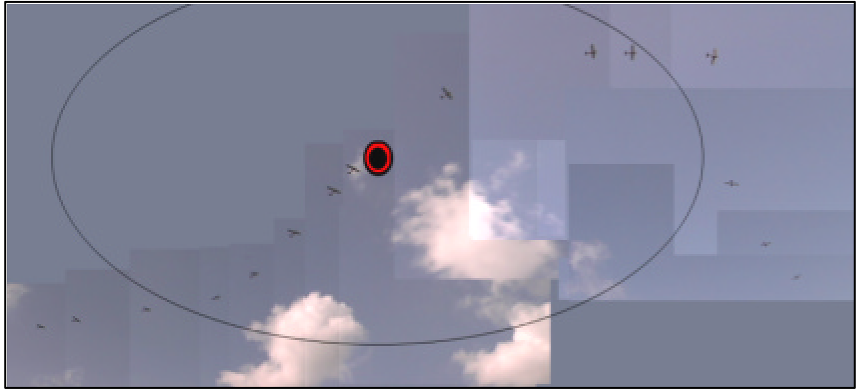


Evasion Example 2





Conclusions



- Successfully demonstrated air-to-ground targeting using a neural network endgame targeting reflex
- Reflex is capable of directing target strike for targets moving on rapidly changing, evading and unpredictable paths
- Reflex is capable of working through sensor disruptions
- Demonstrated reflexive target seeking and avoidance algorithms can work on a model flight vehicle

Reflex Adaptability

- Minimal Autopilot System (decoupled open loop)
- 1/3 to 1/2 second delay in the rate loop.
- Unpredictable dynamics and orientations
- Unpredictable moments due to wind gusts